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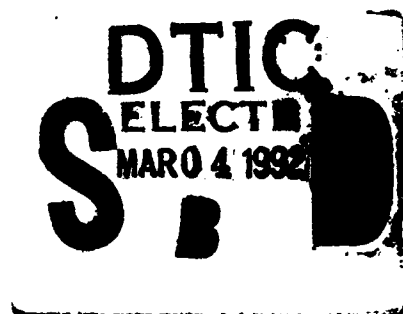
TRADE STUDY OF THREE OXYGEN PROCESSORS FOR
THE MARTIAN ATMOSPHERE

by

Steven R. Plystak

SEPTEMBER 1991

Thesis Advisor: Dan C. Boger

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This thesis is focused toward the Mars atmosphere and its potential resource use for life support systems which provide oxygen to astronauts during all phases of a mission. The weight required to send numerous oxygen tanks to Mars would drastically increase the cost of the mission and might even take up space in the rocket for other needed items on Mars. The solution to this problem is to design a processor that will convert Martian resources to oxygen. Utilization of resources to support life in the Martian environment is performed through the development of life support systems. Life support systems which provide oxygen belong to the Air Revitalization functional area of the Environmental Control Life Support System for Space Station Freedom which will be analyzed in this thesis.

Since the Martian atmosphere is primarily composed of carbon dioxide, this thesis will look at three oxygen processors under development which will convert carbon dioxide to oxygen. These three candidate technologies are the Electrochemical Oxide Cell, Sabatier, and Bosch carbon dioxide reductors. The oxide cell is a self-containing carbon dioxide to oxygen system, but the other two produce water. This suggests that other subsystems must be attached to the output to produce oxygen from water. A trade study is performed using parameters such as power, weight, mass, etc. in order to find the most suitable oxygen processor for the Martian atmosphere. The trade study is a leverage analysis used by NASA to compare similar systems to find the best one. The trade study suggests that the electrolyte oxide cell is the most effective alternative.

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Trade Study of Three Oxygen Processors for the Martian Atmosphere

by

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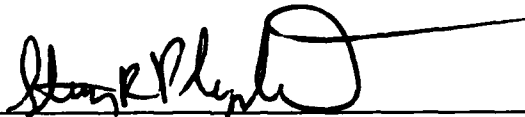requirements for the degree of

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ii

ABSTRACT

This thesis is focused toward the Mars atmosphere and its potential resource use for life support systems which provide oxygen to astronauts during all phases of a mission. The weight required to send numerous oxygen tanks to Mars would drastically increase the cost of the mission and might even take up space in the rocket for other needed items on Mars. The solution to this problem is to design a processor that will convert Martian resources to oxygen. Utilization of resources to support life in the Martian environment is performed through the development of life support systems. Life support systems which provide oxygen belong to the Air Revitalization functional area of the Environmental Control Life Support System for Space Station Freedom which will be analyzed in this thesis.

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iii

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

There are several interesting destinations in the solar system worthy of human exploration. Mars and the Moon have become the two principal choices due to their adaptable humanistic environment and our technological feasibility to reach them. Of the two, Mars will emerge as the primary goal of the 21st century. The best way to achieve this goal of human exploration is by way of space stations and permanent lunar outposts [Ref. 1:p. 475].

On July 20, 1989, President Bush outlined an agenda for future space travel. "First for the coming decade, for the 1990s, Space Station Freedom, our critical next step in our space endeavors. And next, for the next century, back to the Moon, back to the future, and this time back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars. Each mission should and will lay the groundwork for the next." [Ref. 1:p. 475]

The President did not project a precise timetable to obtain those commitments but rather established sequential steps such as the Space Station Freedom and the Lunar Outpost for installing living and working quarters in space followed by a Mars outpost [Ref. 1:p. 475]. The President firmly set the philosophy and general direction of the National Aeronautics and Space Administration for the years to come.

The main focal point of this thesis will be our future mission to Mars as set forth by President Bush. It will flow, by chapter, similar to basic top down design theory. The

second chapter presents some important facts about Mars necessary to achieve a manned mission and, hopefully, colonization on Mars. From this, valuable Martian resources required to establish an outpost are analyzed which will be brought out in Chapter III. Chapter IV will center on one important component of the Martian resources and its possible transformation to a useful life support system needed on Mars. The final, and probably most important, part of this thesis will be a trade off study using reliability, mass, volume, power, etc. to find the best life support system for the job. In summary, this thesis will begin with a look into the Mars mission in general and end with a valuable design needed to fulfill important requirements for Mars colonization.

II. BACKGROUND

Humans have been observing and exploring Mars for quite some time now. This has resulted in our creating a databank on the many characteristics of Mars necessary to initiate the planning process for colonization. This information has been obtained through simple earth telescope observations, earth radar, and the Mariner and Viking missions. The results have been astonishing for all those concerned.

A. EARLY MARS EXPLORATIONS

Many Martian characteristics were surmised by scientists years ago. The seventeenth century star gazers thought they were looking at seas and another continent. In the eighteenth century, polar caps were observable to the human eye through a telescope. Our primitive instruments and our imagination told us Mars was much warmer than it is, had more atmosphere than it does, and had an ample amount of water. Some of the truth surfaced with the development of advanced telescopes in the twentieth century. They told us that the Martian atmosphere was actually thin, devoid of oxygen, and much colder than Earth. Some other basic physical properties determined by telescopes were the length of a Martian day, distance to the sun and earth from Mars, its radius, etc. [Ref. 2:p. 12].

The Mariner 4 spacecraft, which was launched in the early 1960s, took 22 photographs of a small area on the Martian surface. They showed a bleak, cratered terrain, a harsh, dead planet [Ref. 2:p. 12].

Mariner 6 and 7 photographs taken in the late 1960s showed that parts of the Martian surface were covered with heavily cratered plains and showed little sign of geological activity. It resembled the moon's surface except for the frost found on the crater rims. From these pictures, scientists concluded that there weren't any habitable living conditions on Mars [Ref. 3:p. 12].

On May 30, 1971, Mariner 9 left earth's orbit and arrived in Mars orbit in November. The spacecraft had two highly sophisticated cameras on board, and its mission was to map most of the Martian surface, not just a small area as did the previous Mariner missions. A major dust storm obscured the surface for several months; nevertheless, it finally dissipated and the entire surface was photographed. Mountain peaks, great volcanoes, valleys, potential river systems, islands, step cliffs, etc. were seen and documented by scientists [Ref. 2:p. 13]. In summary, the southern hemisphere is mostly cratered highland and the northern hemisphere is dominated by lowland plains [Ref. 3:p. 52]. The two moons of Mars, Phobos and Deimos, were also photographed with clarity [Ref. 3:p. 58].

On August 20 and September 9, 1975, two Viking probes departed earth's surface and headed to Mars. Each Viking consisted of two parts: an orbiting satellite to photograph the Martian surface at high resolution (100,000 times better than previously) and a lander to separate from the orbiter and hurtle down to the Martian surface [Ref. 3:p. 41]. Their instrumentation included stereo cameras, three different life detection experiments, a meteorological station, equipment for measuring the organic-inorganic composition of the atmosphere and very small surface particles called fines, a

seismometer, and instruments for evaluating the magnetic and physical properties of the soil. The two identical landers of Viking I and II were placed on nearly opposite sides of the northern hemisphere of Mars [Ref. 4:p. 2].

The weather was first monitored via temperature variations, wind speeds and directions, and barometric pressures [Ref. 2:p. 43]. Relative humidity varies from .1% in the daytime to 100% at night. Nonetheless, due to extreme coldness, Mars is drier than the driest spot on earth [Ref. 4:p. 4]. The most vivid detailed pictures of the surface were taken; objects of 1mm across were seen with much clarity. Many people compared these views to parts of Death Valley and Painted Desert USA [Ref. 3:pp. 43]. All the data received from these spacecraft sparked our initial curiosity of sending manned missions to Mars in the future.

B.   MARS' CHARACTERISTICS

Mars is like a frozen desert. Its surface is sand and rock and somewhat resembles the Sahara, but its ground is completely frozen as is Antarctica. As harsh as Mars may be, it is by far the most pleasant and earthlike world in the solar system, and experiments duplicated on earth to resemble a Mars environment have proven that some forms of life can survive there. In a nutshell, Mars can clearly be called our sister planet. True, it is much colder than earth, has no greenhouse effect, and its atmosphere is without any oxygen, but history has proven that certain life forms can adapt in this type of environment. Mars somewhat resembles the earth during evolution [Ref. 3:pp. 39-40].

Mars is approximately 1.52 AU, or 228,000,000 km, from the sun. It only receives about half the sunlight as the surface of the earth. The mass of Mars is about one-tenth and its surface gravity is .38 of planet earth. Since Mars has no magnetic field, it is subject to solar activity such as flares, radiation, ultraviolet light, etc., much more than is earth. The length of day is just a little more than earth's and a year is twice as long. Some of the physical properties of Mars are summarized in Table 1 [Ref. 5:p. 1].

TABLE 1. PHYSICAL PROPERTIES OF MARS

Property	Mars	Earth
Mars	6.418E23kg	5.986E24kg
Equatorial Radius	3397.2 km	6378.4 km
Surface Gravity	3.73 m s-2	9.80 m s-2
Escape Velocity	5.02 km s-1	11.18 km s-1
Radius of Stationary Orbit	20,430 km	42,240 km
Surface Temperature Range	130 to 300 K	220 to 300 K
Mean Temperature	215 K	288K
Surface Pressure	6 to 15 mb	1 bar
Albedo	.25	.3
Solar Day (1 "sol")	24h 39m 35.238s	24h
Sidereal Year	686.97964 days, 668.59903 sols	365.26 days
Obliquity of axis	25 deg	23..5 deg
Eccentricity	.0934	.0167
Mean Distance to Sun	1.52 AU (2.28E8 km)	1 AU (1.49E8km)

The Mars atmosphere is shown in Table 2. It shows a predominant amount of carbon dioxide. Traces of nitrogen, argon, oxygen, carbon monoxide, and water vapor make up the remaining gases. The composition of atmospheric dust is composed of small grained surface soil blown into the air by the tremendous Martian winds [Ref. 5:pp. 1-2]. Dust storms tend to originate in the southern hemisphere at times near perihelion and

6

TABLE 2. COMPOSITION OF MARS

Gas	Concentration	
	Mars	Earth
CO_2	95.3%	0.03%
N_2	2.7%	78.08%
Ar	1.6%	0.93%
O_2	0.13	20.9
H_2O	0.03*	2*
CO	0.07	0.12 ppm
Ne	2.5 ppm	18 ppm
Kr	0.3 ppm	1.1 ppm
Xe	0.08 ppm	0.087 ppm
O_3	0.003*	40 ppm
Other		< 7 ppm
Dust	10 ppm	------

* variable

southern summer solstice. High winds near 100 m/s instigate the lofting of dust during a major dust storm. The dust is carried around Mars with a maximum wind speed of 10 m/s [Ref. 5:p. 2].

There is a vast amount of evidence to indicate the past presence of water. Valley networks suggest that there may have been rain. Other evidence includes the outflow channels, which appear to have been formed from the sudden release of water. On some occasions, water frost was observed at the Viking Lander site at 48 degrees North latitude. The largest amount of water vapor in the atmosphere has been observed in the northern latitudes above 60 degrees [Ref. 5:p. 2].

The polar caps of Mars consist of seasonal and residual caps. Seasonal caps only occur in the winter and are formed from the condensation of atmospheric carbon dioxide. Residual caps persist throughout the year and are composed of water ice. A permanent polar cap located in the northern part of Mars has a diameter of 1000 km and is composed of ice deposits [Ref. 5:p. 2].

The composition of the surface has been analyzed by the two Viking Landers. Based on the results of the Viking I Lander site, the most likely distribution of compounds have been identified in Table 3. Their mineralogy states were not determined but upon chemical consideration, the mineralogy of most of the elements has been inferred in Table 4 [Ref. 6:p. 152]. The sum is important because it shows that 8.2% of the inferred states has not been directly detected. This remainder includes such compounds as nitrogen oxides, water, carbonates, etc.

The Viking X-Ray Fluorescence Experiment found the approximate percentage of elements with atomic number 12 and above. There was no direct detection of hydrogen, nitrogen, carbon, or oxygen, but these elements do exist in other compounds. Almost all the elements were assumed to be in the form of oxides [Ref. 6:p. 193]. Other compounds not directly detected but assumed to exist are water, sodium oxide, carbon dioxide and nitrogen oxides [Ref. 6:p. 152]. Carbonates that may exist from Viking element analysis are calcium carbonates, magnesium carbonates, iron carbonates, manganese carbonates, and calcium- magnesium bi-carbonates [Ref. 6:p. 193].

Some other physical properties of the Martian soil that have been determined are shown in Tables 5 and 6 [Ref. 5:p. 4].

8

TABLE 3. ELEMENTAL COMPOSITION OF THE VIKING I LANDER SITE

Element	Percent by Mass
Mg	2.5 - 7.5
Al	2.1 - 3.9
Si	18.4 - 23.4
S	2.6 - 3.6
Cl	0.4 - 1.0
K	< 0.25
Ca	3.2 - 4.8
Ti	0.3 - .7
Fe	10.7 - 14.7
L*	45.8 - 54.4
X**	0.6 - 16.2
Rb	< 30 ppm
Sr	30 - 90 ppm
Y	40 - 100 ppm
Zr	< 30 ppm

*   L is the sum of elements not directly determined

**   If the detected elements are all present as their common oxides (Cl excepted) then X is the sum not directly detected, including H_2O, NaO, CO_2, and nitrogen oxides

TABLE 4. INFERRED MINERALOGY OF THE VIKING I LANDER SITE

Compound	Percent by Mass
SiO_2	44.7
AL_2O_3	5.7
Fe_2O_3	18.2
MgO	8.3
CaO	5.6
M_2O	< 0.3
TiO_2	0.9
SO_3	7.7
Cl	0.7
SUM*	91.8

*   Assuming K_2O is counted as O

TABLE 5. THERMAL AND DIELECTRIC PROPERTIES
OF THE MARTIAN SOIL

Average Visible Albedo	.25, Range: 0.09 - 0.43
Surface Thermal Inertial	1.6 - 11 * 10^{-3} cal/ cm^2 $s^{1/2}$ K
Specific Heat Capacity	.0145 cal / gm - K
Thermal Conductivity	2 * 10^{-4} cal / cm - s - K
Thermal Emissivity	1
Dielectric Constant	2.3 - 3.5

TABLE 6. MECHANICAL PROPERTIES OF MARTIAN SOIL AND ROCK

Property	VL-1, Sandy	VL-1, Rocky	VL-2
Bulk Density, kg / m^3			
Soil	100 - 1600	1200 - 1600	1100 - 1480
Rock		2900	2600
Particle Size %			
> 2 cm	0	25	20
Clods and fines	100	75	80
Cohesion of rock, N / m^{-2}	-----	> 10^4	> 10^4
Cohesion of soil, N / m^{-2}	10 - 100	10 - 10^4	10 - 1000
Angle of internal friction, deg	30 - 45	30 - 45	30 - 45
Penetration resistance, N / m^{-3}	3 * 10^5	6 * 10^6	6 * 10^6
Adhesion, N / m^{-2}	1 - 100	-----	-----
Coefficient of sliding friction	0.3 - 0.5	0.3 - 0.5	-----

C.   MOTIVATIONS FOR MARS COLONIZATION

What is the motivation for establishing a manned colony on Mars? Some of it can

be formulated from all the data extracted from the previous sections covered thus far.

Mars has more similar characteristics to the planet earth than any of the other planets in

the solar system. With the appropriate technology of spacecraft and life support systems,

many scientists believe that the planet can be made habitable. With this in mind, questions may be answered in much the same way as our own theories on the evolution of planet earth.

1. Scientific

Mars provides some unique scientific advantages not to be found elsewhere in the solar system. Mars is the only planet in the solar system that we know of with an appreciable surface and atmosphere for life. This will allow numerous planetology studies in geophysics, geology, meteorology, etc. Mars is the best planet of all for these studies because it offers the possibility of important research on the chemical evolution and origin of life in the past, a possibly more hospitable climate, and studies on the response of terrestrial organisms in the harsh environments. The development and study of synthetic ecosystems and an entire biosphere offers an important opportunity [Ref. 7:p. 23].

2. Engineering

The use of Martian resources to establish a habitable environment can only be achieved through numerous engineering processes. Creating life support systems, mining equipment and techniques, propellant and power plants, and just the means to go to Mars and back are some of the advancements in technology that can be gained with the Mars mission.

3. Political and Strategic

If the United States took the first steps to achieve colonization of Mars, then it would assume a dominant role in all aspects of development and utilization of space.

The United States would then maintain the highest position in international space discussions and space law. At home, the Mars mission would create a booming national industry. The economic benefits of a Mars settlement would be tremendous. The boosted technology will increase overall investments in space and accelerate the commercial use of space. The federal government's leadership ability would significantly improve since a popular national goal would be created and executed. A Mars settlement would also provide us with an important national asset. It would build up our reserves of scarce materials, extend our political and cultural system philosophies to space, establish a new element in our strategic and military way of thinking, and provide us an outpost for further explorations into the solar system [Ref. 7:pp. 22-24].

4. Other

An overall public appeal would be felt if we colonized Mars. Public identification with the space program is important. Knowing what it is like to feel zero gravity in space is harder to comprehend than observing an astronaut in a rover driving to the edge of a cliff to see what's on the other side. The exploration of space has always appealed to this nation and tends to give us a sense of accomplishment and pride. The public interest in watching astronauts on Mars would probably exceed anything experienced before.

D. FEASIBILITY OF COLONIZATION

When President Bush made that speech on July 20, 1989, he set the entire space community on an arduous path. Many reports surfaced establishing the framework for a Mars colony. This section will just touch on a few ideas presented in two reports.

1. Three steps to achieve colonization

In order to establish a permanent colony on Mars, three exploration steps must be achieved. The first is the development and insertion of Space Station Freedom in space. It will provide the essential scientific and technological foundation for later human missions to the planets. Physiological and psychological effects of low gravity and long term habitation of the space environment will be studied on Freedom [Ref. 8:p. 3-1].

The next step will be to build a permanent outpost on the moon to establish a human presence for science and exploration. The lunar outpost will serve as a test bed for verifying critical mission systems, hardware, technologies, human capability and self sufficiency, and operational techniques that can be applied to further exploration [Ref. 8:pp. 3-1,3-2].

The third step will be to send a series of robotic spacecraft to Mars in order to provide scientific and engineering data to support selection and certification of the expeditionary and permanent outpost sites; to return a sample of Mars to earth for scientific analysis and determination of the potential of back contamination, to conduct studies that diminish risks to human explorers; to provide data to assist in designing piloted vehicles and surface systems: to search for Martian resources; and to generally

demonstrate readiness to proceed with a human Mars mission. The first robotic mission to Mars is scheduled for 1992 [Ref. 8:p. 3-2].

2. Three phases of colonization

The development of a lunar and mars colony has been broken down into three phases -- emplacement, consolidation, and utilization; each of these represents a progressively higher level of commitment, understanding and capability [Ref. 9:p. 8].

The emplacement phase includes the initial establishing of human presence on Mars. A planned crew of four would stay on the Martian surface for 30 days and conduct numerous experiments and exploratory missions. The next piloted flight of five would replace the others and stay on Mars for 16 months. Their objectives would be to demonstrate the feasibility of long term habitation on Mars, send propellent product plants to Phobos, and conduct intensive investigations of areas around the outpost [Ref. 9:p. 8].

The consolidation phase includes continuing the permanent human presence on Mars. Two piloted flights would occur during this phase for 18 months each. Phobos exploration, expanding exploration on Mars, and scientific activities would be achieved in this phase [Ref. 9:p. 9].

The utilization phase's primary objectives would be to use local Martian resources to produce oxygen and to continue to develop operational experience living and working independently in an extra-terrestrial environment. A proposed crew of seven would stay 21 months on Mars in this phase [Ref. 9:p. 9].

3. Technology assessment

A major challenge, according to one case study, for human settlement on the moon and Mars is the need to reduce the total mass that must be launched into low earth orbit and transported to the lunar and Mars surfaces. Critical technologies in regenerative life support, aerobraking, and advanced space-based cryogenic engines must be developed to reduce mass in the near term. Mid-term technologies to decrease mass are radiation shielding, surface nuclear power, and in situ resource utilization. These six technologies need to be accelerated in order for the mission to happen. Other advancements are needed in space operations, earth to orbit transportation, space transportation, surface systems, space effects on humans, and in lunar-Mars science [Ref. 8:pp. 8-3, 8-16].

E. TIMETABLE OF EVENTS

Figure 1 [Ref. 10:p. 3] is a projected timetable created by one NASA report.

F. PROPOSED OVERALL COST

From several standpoints, a manned Mars landing program would be very cost effective as compared to previous space programs. The total cost of the Apollo missions in 1981 dollars was $62.9 billion and the projected Mars mission cost in 1981 was $19.60 billion [Ref. 7:p. 290]. For an American to land on Mars would require only one-half of the annual expenditures required to land a man on the moon, or less than 1% of the annual national budget at the peak year of the program. The program would be expected to cost in total no more than two-thirds of the manned lunar landing or 1% or less of one year's GNP spread over 12 years. In any one year, only one tenth of one percent or less

Phase	Dates	Notes
Precursor	1965 - 2016	- Obtain Environmental knowledge necessary for human exploration - Identify and characterize sites
Emplacement	2016 - 2024	CHARACTERISTICS - First few human missions - Human landings at several sites - Limited human mobility (10 km) - No resource utilization - Small crew (5) - Short stays (30 days) - Lander is habitat ACTIVITIES - Local exploration by humans - Teleoperated "fetch" rovers over 100 km range - Sample collection, limited analysis
Consolidation	2024 - 2034	CHARACTERISTICS - Crew overlap - Begin resource utilization - Base construction underway ACTIVITIES - Expeditions in pressurized rover over 100 km range - Teleoperation/presence over regional distances - Extensive sample analysis
Utilization	2030 -->	CHARACTERISTICS - Permanent base - Self sufficiency - Global point-to-point access ACTIVITIES - Spawning "Emplacement Phase" remote bases - Global scale telepresence with sample return to base - Complete capability for sample analysis

Figure 1. Elements of Mars Exploration

would be going to this program. On a per capita basis, it would cost each American about

$100 or one-third the cost of the lunar landing. This is possible because of the low risk

of building on existing space technologies [Ref. 7:p. 292].

III. MARTIAN RESOURCE REQUIREMENTS AND THEIR UTILIZATION

As mentioned earlier, Mars has an abundance of resources capable of sustaining life for astronauts on Mars. The four essential requirements necessary for most missions on Mars, air, water, fuel, and food, will be covered in this chapter.

The two main sources for these on Mars are the atmosphere and soil. In order to make these resources useful, adequate life support systems are needed, and some types of these systems will also be discussed in this chapter.

A. ATMOSPHERE

The atmosphere, as noted before, contains around 95% carbon dioxide. Nitrogen, argon, oxygen, carbon monoxide, and water vapor also make up trace amounts. Through simple gas processing, these materials can be made useful to astronauts performing a specified mission on the surface of Mars.

1. Breathable Air

The normal requirement for oxygen respiration is at a rate of .83 kg/ per man-day [Ref. 11:p. 2]. The amount of air required for a certain mission on Mars varies and is people dependent. An example is that more air output is required for a habitat of eight men than one in a space suit walking on the Mars surface. Breathable air must contain adequate partial pressures of oxygen along with an inert buffer gas. In the atmosphere, there is a suitable partial pressures of diatomic oxygen. Nitrogen and argon

can be used as the inert buffer gas since carbon dioxide has toxic effects on the blood buffer system above partial pressure of about 10 millibars. The gases must go through a series of compression cycles in order to obtain the desired partial pressures and through an added condensation cycle to remove the carbon dioxide [Ref. 12:p. 4]. Electrolysis of water and carbon dioxide reduction techniques for oxygen recovery under development now show promising results [Ref. 13:p. 3].

2. Water

The daily human water requirement for drinking is 1.62 kg/day [Ref. 14:p. 12]. The amount of water in the Martian atmosphere is variable and dependent on location and time of day. Figure 2 is a contour plot of water vapor abundance in the Martian atmosphere as a function of latitude and longitude over time. Shaded areas are unreliable data regions. The values range from 1 to 90 precipitable microns, and this means if all the water in the atmosphere were condensed into liquid water, it would only be 1 to 90 microns thick. This value is 10,000 times smaller than the values typical for earth's atmospheric moisture content. The largest amount of water is seen at latitudes of about 60 degrees and at low elevations. The wettest season seems to be during the northern hemisphere summer.

Figure 3 shows the annual average water vapor in the Martian atmosphere as a function of latitude and longitude. The lowest place in the southern hemisphere (-45 degrees south, 290 degrees west) has the largest average column abundance of water vapor and its peak has more than twice the column water amount than any other place on the planet [Ref. 6:pp. 150-151]

18
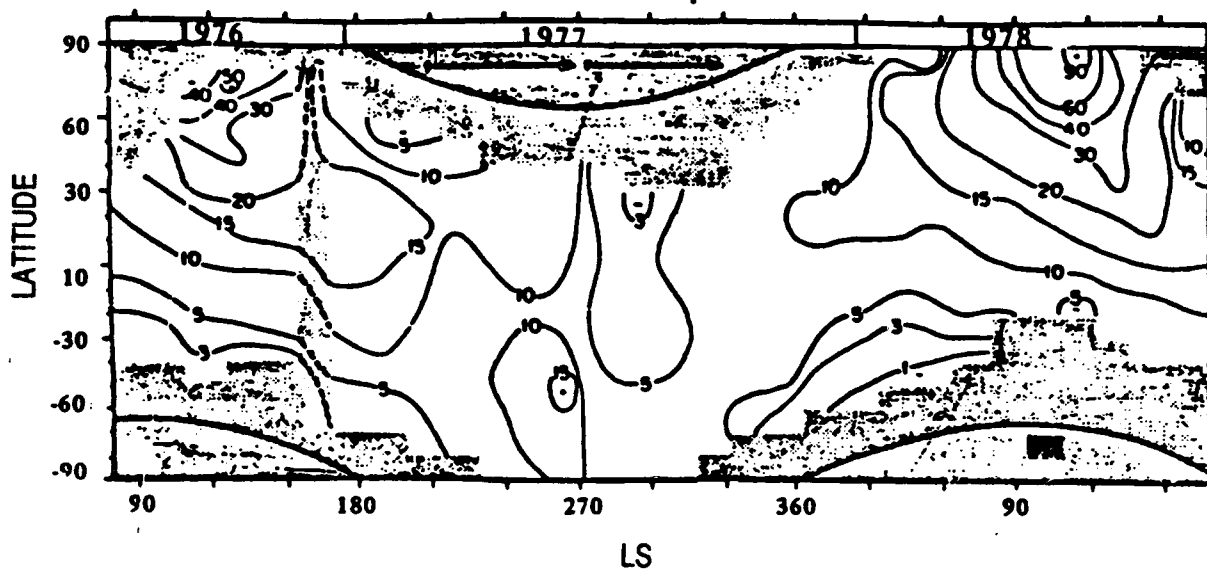
Figure 2. Water Vapor Abundance in the Martian Atmosphere
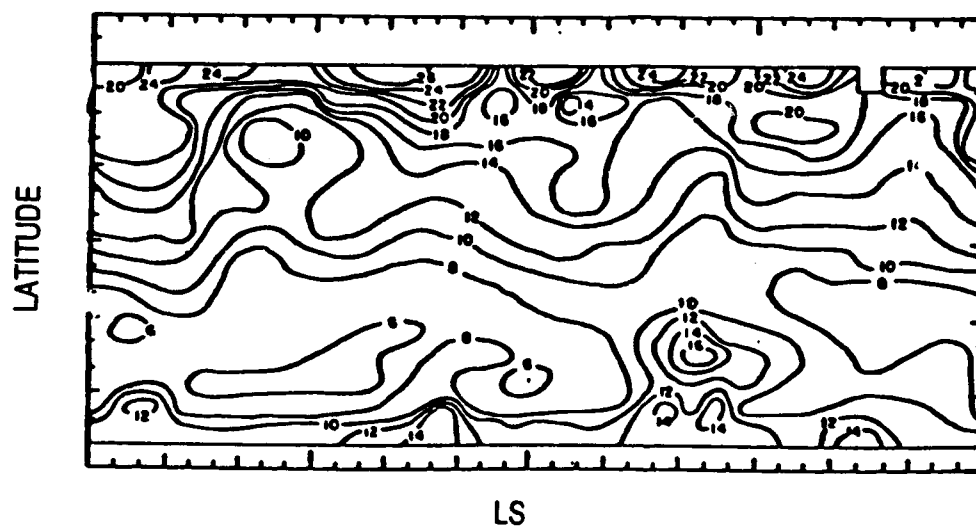
Figure 3. Annual Average Water Vapor in the Martian Atmosphere

Even though the values of water are relatively small compared to earth, the total amount of water vapor in the Martian atmosphere, about 360 million gallons, is huge compared to the requirements of a human research base.

19

Time of day also places an important role for moisture content. Table 7 shows the concentration of water in the Martian atmosphere over a range of frost points and partial pressures in micron-bars (the temperature at which the atmosphere is saturated) [Ref. 6:p. 150].

TABLE 7. MAXIMUM WATER CONCENTRATION IN THE MARTIAN ATMOSPHERE VS. FROST POINT TEMPERATURE

Frost temperature (degrees C)	Atmospheric Water	Partial Pressure of Water
-40	1.6%	129 u6
-50	0.49	39.4
-60	0.135	10.8
-70	323 ppm	2.59
-80	66.7 ppm	0.53
-90	11.7 ppm	0.09

As the sun rises and increases temperatures, the water moisture content increases due to evaporation of surface ice. During the night at temperatures around minus sixty degrees, the air becomes saturated and the excess water condenses as frost. So the water quantity in the atmosphere remains at equilibrium with a large reservoir of water ice on the poles [Ref. 12:p. 273]. If one assumes 100% humidity at a nighttime temperature of -60 deg C, the volume of air which contains 1 kg of water has been calculated to be 9.1E10 cubic centimeters.

The water can be taken out of the atmosphere several ways. One way is by adiabatic compression which ensures a partial pressure of water to exceed the saturation vapor pressure. This causes water to condense and the amount is equal to the decrease in volume. The amount of power required to take out 1 kg of water is 33kw-hrs. Another

way to take out water is by a turbine compressor which operates on a daylight compression cycle with condensation and collection occurring at night [Ref. 12:p. 3]. A schematic for extracting water by compression and cooling is shown in Figure 4 [Ref. 15:p. 227].

DRIED
AIR

SYSTEM PRESSURE: 12 atm

EXPANDER

COUNTERFLOW
HEAT
EXCHANGER

CONDENSER
$pH_2O = 16mb$ $pH_2O = 7mb$
$T = 15$ deg C $T = 0$ degr C

COMPRESSOR

H_2O

MOIST RH = 1%
AIR   T = -20 degr C
P = .008 atm

COOLING

LIQUID H_2O
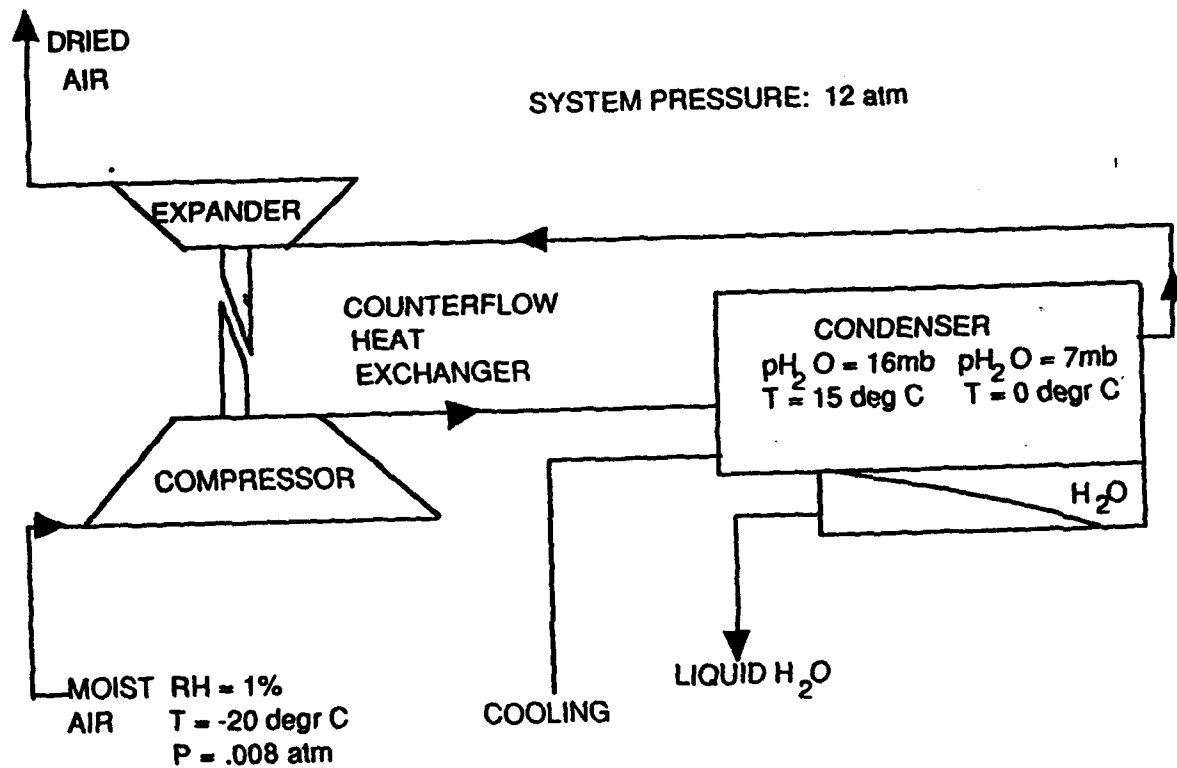
Figure 4. Schematic of Subsystem for Removing Water
from the Martian Atmosphere

3.   Fuel

Because of the exorbitant amount of propellant required to perform the Mars missions, it would be more beneficial to manufacture propellants from the Martian resources. These chemical propellants would be needed for frequent landing and

ascending to the Martian surface since high performance space drives (e.g., thermonuclear, anti-matter) necessary for long distance travel cannot do this job. There are four options for generating propellant from the atmosphere. The first one is to collect oxygen from the atmosphere and burn it with fuel brought from Earth or use a oxygen/ carbon monoxide combination. Another option is to use Martian water if large quantities exist with the carbon dioxide atmosphere for synthesis to produce an oxygen/methane propellant combination. Another possibility is an oxygen/hydrogen mixture but the liquefying and storing of hydrogen would be difficult on Mars. Of all these options, the burning of Earth fuel and oxygen/carbon monoxide propellant seems to be the best option. The oxygen/methane fuel requires more water than the atmosphere can provide for manufacturing it and the abundance of soil water is not known exactly [Ref. 6:p. 167]. Table 8 represents the specific performance of three options [Ref. 6:p. 168].

TABLE 8. PROPELLANT COMBINATION PERFORMANCE

PROPELLANT	SPECIFIC IMPULSE
O_2/CO	2550 m/sec (260 sec)
O_2/CH_4	3530 m/sec (360 sec)
O_2/H_2	4320 m/sec (440 sec)

The best performance from this table is the oxygen/hydrogen propellant. The oxygen/carbon monoxide values are not that impressive and the oxygen/methane has almost a 20% penalty in performance, but this may be offset by the greater density of this propellant. Another way to evaluate the options is by comparing their mass ratio (lift -off mass to mass remaining at engine shutdown) as in Table 9 [Ref. 6:p. 168].

22

TABLE 9. MASS RATIO REQUIREMENTS

MISSION	STAGES	MASS RATIO		
LOW MARS ORBIT	1	O_2/CO	O_2/CH_4	O_2/H_2
		6.07	3.6	2.90
V = 4.6 km / sec	2	2.46	---	---
EARTH RETURN	1	13.3	6.4	4.61
V = 6.6 km / sec	2	3.64	2.55	----

From this table, it is apparent that the oxygen/hydrogen combination can perform the mission with only one stage. The oxygen/methane fuel can perform the Mars mission orbit with one stage but would benefit from staging for Mars orbit and escape. The oxygen/carbon monoxide fuel also demands staging for orbit and escape. In summary, options oxygen/carbon monoxide and oxygen/Earth fuel would be sufficient for the early Mars missions or until there is more water discovered on Mars; then oxygen/methane would be the chosen one [Ref. 6:p. 168].

4. Food

As of now, there is no way to produce food except from plants. The requirement for food on Mars would be .62 kg/man-day [Ref. 14:p. 12]. The concept for manufacturing food is rather an easy one. It requires the atmosphere to be compressed to a few hundred millibars. The Martian air is then sent through a low pressure greenhouse where plants and algae fix nitrogen while they are growing. Plants are nourished by carbon dioxide. Their requirements also include quantities of nitrogen/air buffer, oxygen, and water which are all present in the atmosphere [Ref. 12:p. 5]. Experiments with some vegetable seeds maintained in a low pressure 50 millibar water-saturated carbon dioxide

atmosphere here on earth proved that plants can grow. The experiments concluded that exposing the plants to a carbon dioxide atmosphere can result in an increased photosynthetic rate, and productivity could be optimized [Ref. 16:p. 190-191]. The reasons for using a low pressure plastic greenhouse is because high pressure ones of 1 bar are extremely expensive, difficult to service and maintain, and are bulky and cumbersome to transport to Mars [Ref. 16:p. 189].

B. SOIL

The Viking Lander Spacecraft determined after doing several experiments that the soil contains valuable resources required to support a manned mission to Mars. This section will briefly look at how the soil can be a substantial source for the four essential requirements necessary to achieve the success of the Mars missions; air, food, fuel, and water.

1. Breathable air

The element oxygen, present in water and carbon dioxide, makes up 40% of the Martian soil's weight [Ref. 7:p. 199]. Oxygen can be taken out of the soil upon hydration, but in insufficient quantities to be of any use. The soil is known to contain more water than the air, so electrolyzing the water would be one of the best methods for extracting oxygen [Ref. 4:p. 11]. Reduction of the carbon dioxide in the Martian polar caps is another way and the processes which do this are the Sabatier, Bosch, Electrolyte cell, etc. [Ref. 7:p. 199]. A final method not mentioned yet is by simply using the oxygen generated by plants during photosynthesis.

24

2. Water

The soil contains 1-3% water by weight and the subsurface, up to a few meters deep, could contain up to 15% water. This makes the soil a substantially better source of water than the atmosphere. The Viking Spacecraft showed that water is released upon heating the soil. A thermal power source of less than 5 kw or 500 degrees celsius can produce one ton of water per month for each 1% of the water in the soil [Ref. 4:p. 12].

The north pole on Mars has a residual polar cap that contains all ice and covers 800,000 square km. Its average thickness is 1 to 100 meters and amounts to at least 800 billion tons of ice [Ref. 7:p. 198]. The southern residual cap contains both ice and carbon dioxide and its maximum thickness is 1-2 km. Water is also abundantly present in other forms including absorbed and various chemical states [Ref. 6:p. 151]. The present ground pattern on Mars, such as craters with rims that look like mudslides, suggest a fluid-like flow of soil material. This indicates that a significant amount of ice is present under the soil. This land feature is only present poleward of 40 degrees in both hemispheres indicating permafrost in these areas. This water rich permafrost does not seem to occur near the equatorial regions. The exact fraction of ice in the soil can't be validated, but 5-10% has been suggested as possible. This near surface ice was mostly found within the top few centimeters by the Viking Spacecraft [Ref. 6:p. 151]. Initial calculations show that 10 to 100 metric tons could be extracted per month from dry hydrated soil using a 50 kw thermal source [Ref. 7:p. 198].

3. Fuel

As stated earlier, the carbon monoxide/oxygen and oxygen/methane combinations are the best propellant choices for the various Mars missions. The oxygen for these propellants can be electrolyzed either from water taken out of the soil or carbon dioxide out of the atmosphere. The most important constituent that the soil can provide is water which is essential for the synthesis of methane. The chemical reactions needed to produce oxygen/methane propellant [Ref. 17:p. 714] are as follows:

$$CO_2 + 4H_2 \xrightarrow{\text{catalyst}} CH_4 + 2H_2O$$

$$2H_2O + 2H_2O \xrightarrow{\text{electrolysis}} 4H_2 + 2O_2$$
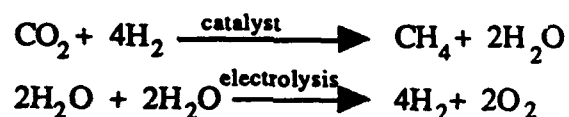
4. Food

The soil, as is the atmosphere, is not a good source for extracting food. Nevertheless; it can provide one of the primary elements necessary for plant growth; that is, water. Since water is more abundant in the soil, it would be a better source for the plants.

C. ADVANCED LIFE SUPPORT SYSTEMS (UTILIZING RESOURCES)

In order for manned space explorations to occur, fundamental functions must be provided in order for astronauts to sustain life outside the Earth's protective environment. Such functions should maintain an adequate environment, provide food and water, and manage waste. Now that we have established that all the elements and compounds needed to support life are found in the Martian environment, the only way to transform them to satisfy those functions is through the development of life support systems. These

26

functions can be separated into two categories, non-regeneration and regeneration. Regeneration functions allow life support resources such as oxygen, water, and food to be potentially reused. Non-regeneration functions do not allow recycling of resources such as make-up for leakage losses, system monitoring, refrigeration control, etc.

An "open loop" system for regeneration functions provides no recovery of life support resources while a "closed loop" system achieves total recycling of these resources. In fully open loop systems, the quantities of resources taken from Earth equal the quantities consumed by the astronauts on a mission. As loop closure starts, quantity needs from Earth are reduced. The degree of closure for life support systems is mission dependent. Reduced resupply from Earth is weighed against system power requirements, cost, volume, etc. This process of designing a system to meet a particular mission's needs has multiple steps and includes the determination of critical life support functions, identification of technologies to provide for these functions, and selection of the technology most suitable for that mission. Evaluation for a particular mission includes variables such as relative cost of power, weight and volume, availability of in-situ resources, resupply capability, as well as crew size and mission duration [Ref. 11:p. 1].

Life support systems now under development for the Space Station Freedom and possibly Lunar and Mars expeditions all belong to the Environmental Control Life Support System (ECLSS) [Ref. 18:p. 1]. The ECLSS is divided into five functional areas; Air Revitalization, Atmosphere Pressure and Composition Control, Cabin Temperature and Humidity Control, Water Reclamation, and Personal Hygiene and Waste Management

27

[Ref. 18:p. 2]. Each of these are further divided into subsystems as shown in Figure 5 [Ref. 18:p. 3].

Cost-effective continuous manned operations in space require the use of three major regeneration techniques; regenerable carbon dioxide removal, reclamation of water, and regeneration of oxygen [Ref. 18:p. 5]. Regenerative ECLSS saves more money than an open loop system; a regenerable electrochemical carbon dioxide removal system will remove about 30,000 lb of carbon dioxide in five years saving $30 million dollars at a Shuttle launch cost of $1000/lb for an open loop system [Ref. 18:p. 3]. Three options of life support in extraterrestrial environments are shown in Figure 6 [Ref. 6:p. 180].

Physical-chemical techniques for regenerating oxygen from carbon dioxide and for producing drinkable water from waste water are under development now. Physical-chemical methods for food generation are also under development now, but promising results for astronaut use are decades away. This indicates that most of the food required for the early Mars missions will have to be transported from Earth.

Early mission planning sets a goal of using biogeneration through the growth of photosynthetic organisms, such as high plants. Plants will regenerate oxygen, remove carbon dioxide and purify water, as well as provide food [Ref. 6:p. 179]. The study of biogenerative life support of photosynthetic plants by NASA became known as Controlled Ecological Life Support System (CELSS). Photosynthetic higher plants absorb light energy and use it to convert carbon dioxide, water, and minerals into oxygen and organic materials. Waste materials produced by plants can be oxidized to carbon dioxide, water, and through various processes. The higher plants used in these processes are wheat,

SPACE STATION
EC/LSS
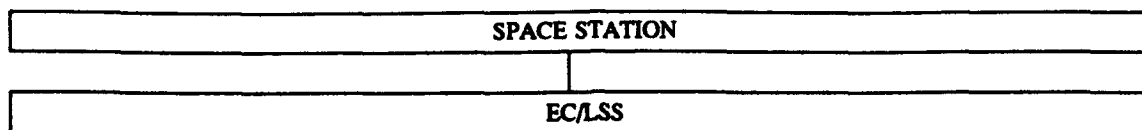
Air Revitalization System
- CO$_2$ Concentration
- CO$_2$ Reduction
- O$_2$ Generation
- Trace Contam. Control
- Atmosphere Monitoring
- Independent Air Rev. Sys.

Atmosphere Pressure & Composition Control
- O$_2$ Storage
- N$_2$ Storage
- N$_2$ Supply (In-flight Gener.)
- Composition Control/Monitor
- Pressure Control
- Airlock Pump
- Dump and Relief
- Pump Down Accumulators

Cabin Temperature & Humidity Control
- Temperature Control
- Humidity Control
- Ventilation/Circulation

Water Reclamation
- Pretreatment
- Water Recovery (Condensate, Hygiene, Urine)
- Post-Treatment
- Water Quality Monitoring
- Biocide Addition/Monitoring
- Water Storage

Personal Hygiene & Waste Management
- Hygiene
- Hand Wash
- Full Body Shower
- Laundry
- Waste Management
  - Toilet
  - Urinal
  - Solids Collection
  - Trash Collector
  - Compacted Solids Storage
  - Conc. Waste Liq. Storage

Figure 5. ECLSS Functional Boundaries
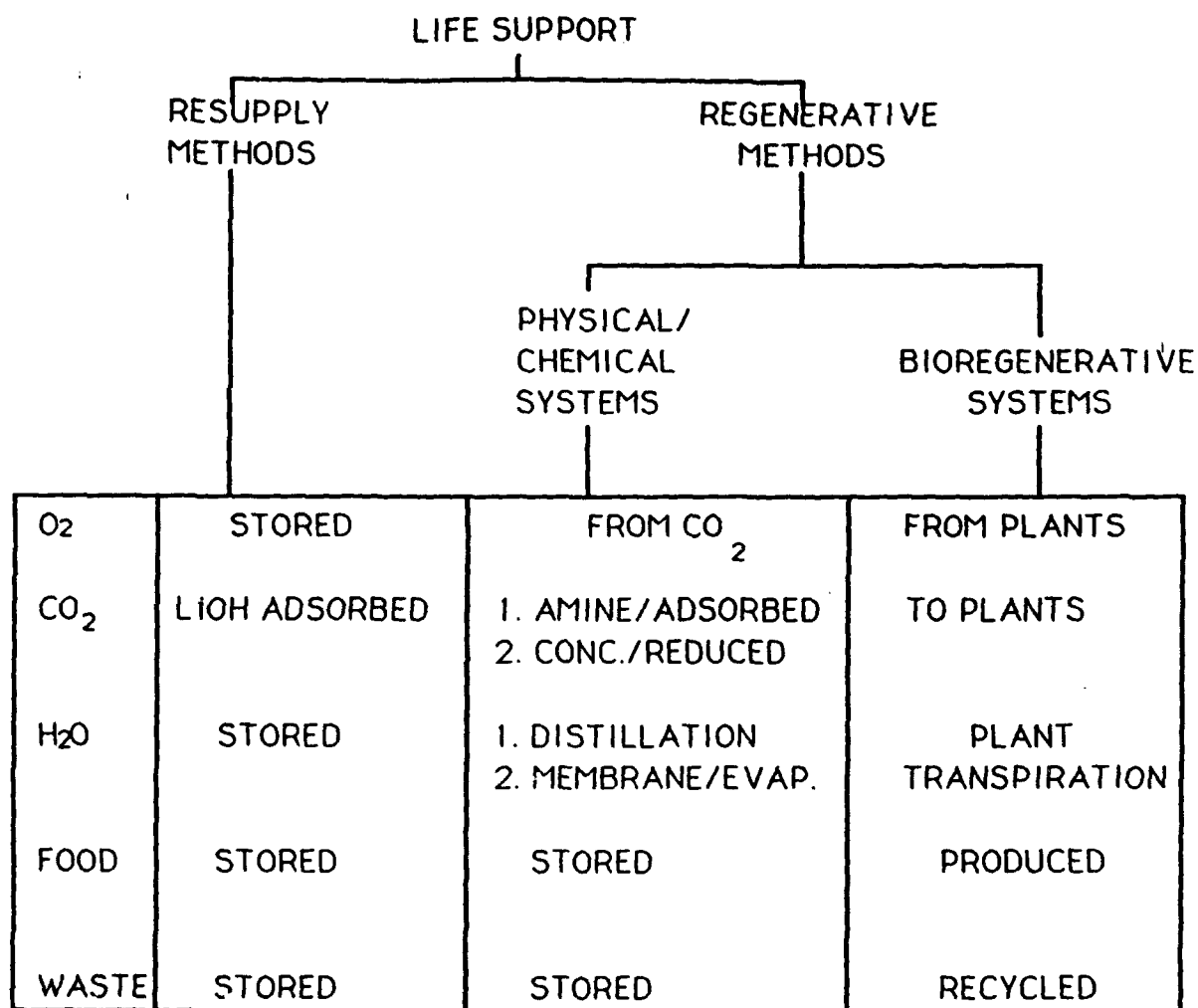
Figure 6. Comparison of Crew Life Support Options

The figure shows a hierarchical diagram:

LIFE SUPPORT branches into RESUPPLY METHODS and REGENERATIVE METHODS. REGENERATIVE METHODS branches into PHYSICAL/CHEMICAL SYSTEMS and BIOREGENERATIVE SYSTEMS.

	RESUPPLY METHODS	PHYSICAL/CHEMICAL SYSTEMS	BIOREGENERATIVE SYSTEMS
O_2	STORED	FROM CO_2	FROM PLANTS
CO_2	LIOH ADSORBED	1. AMINE/ADSORBED 2. CONC./REDUCED	TO PLANTS
H_2O	STORED	1. DISTILLATION 2. MEMBRANE/EVAP.	PLANT TRANSPIRATION
FOOD	STORED	STORED	PRODUCED
WASTE	STORED	STORED	RECYCLED

soybeans, lettuce, tomato, and potato. Advances in algae, which produces protein, are expected in the near future. Figure 7 is a good representation of the flow processes involved while utilizing Mar's resources in a CELSS [Ref. 6:p. 184].

This closed CELSS would be an enclosed modular or compartmental design in order to preclude endangering the entire system even if specific subsystems become
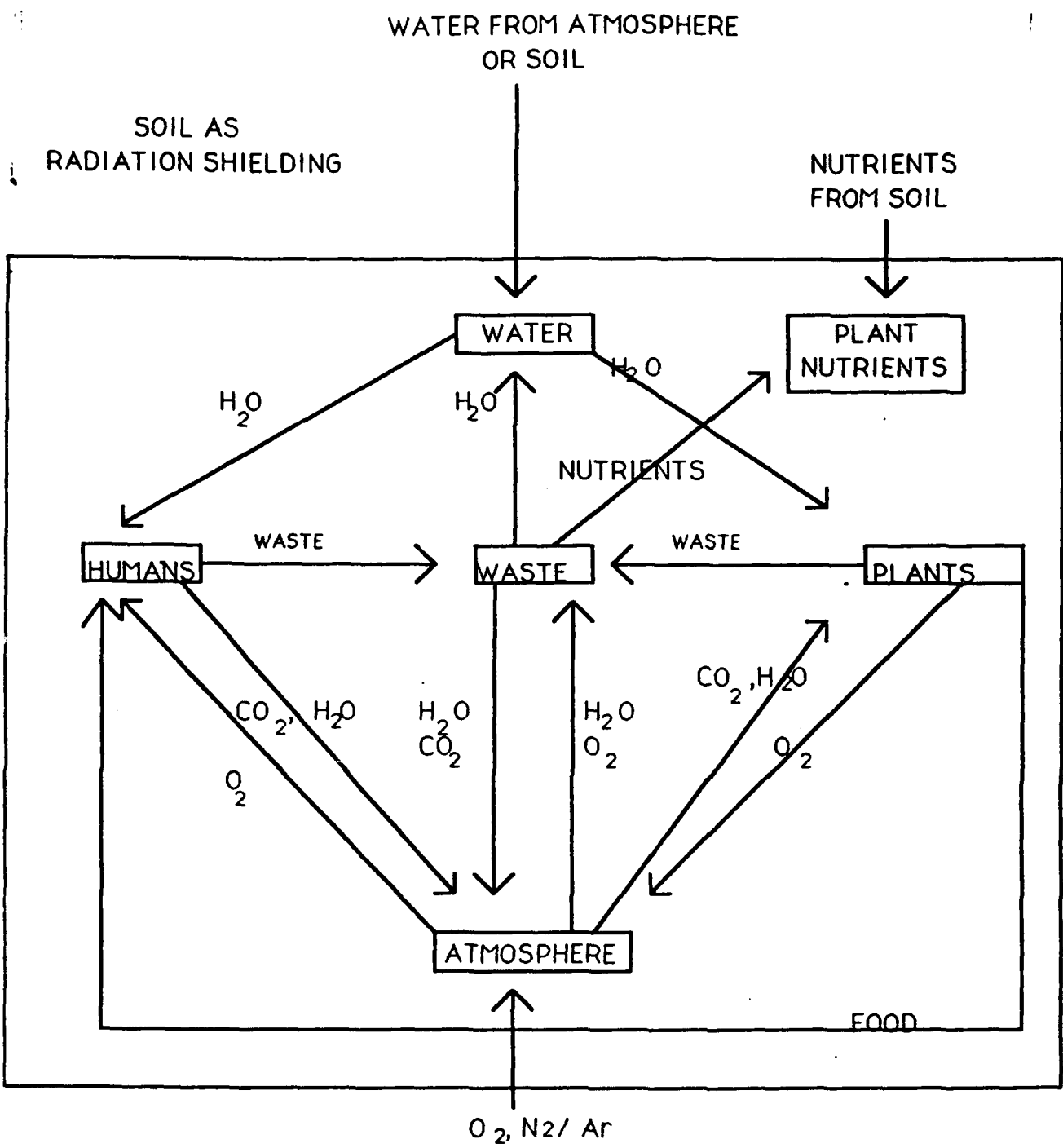
Figure 7. Utilizing Mars Resources in a CELSS

contaminated. Even though the CELSS is materially closed, leakage into the atmosphere is likely and a regenerative system will hopefully rectify this problem [Ref. 6:p. 183].

Using plants is just one way to convert the environment on Mars to something useful for the astronauts. One representation of a life support system which converts all Martian atmospheric elements to useful life sustaining products is portrayed in Figure 8 [Ref. 13:p. 2].
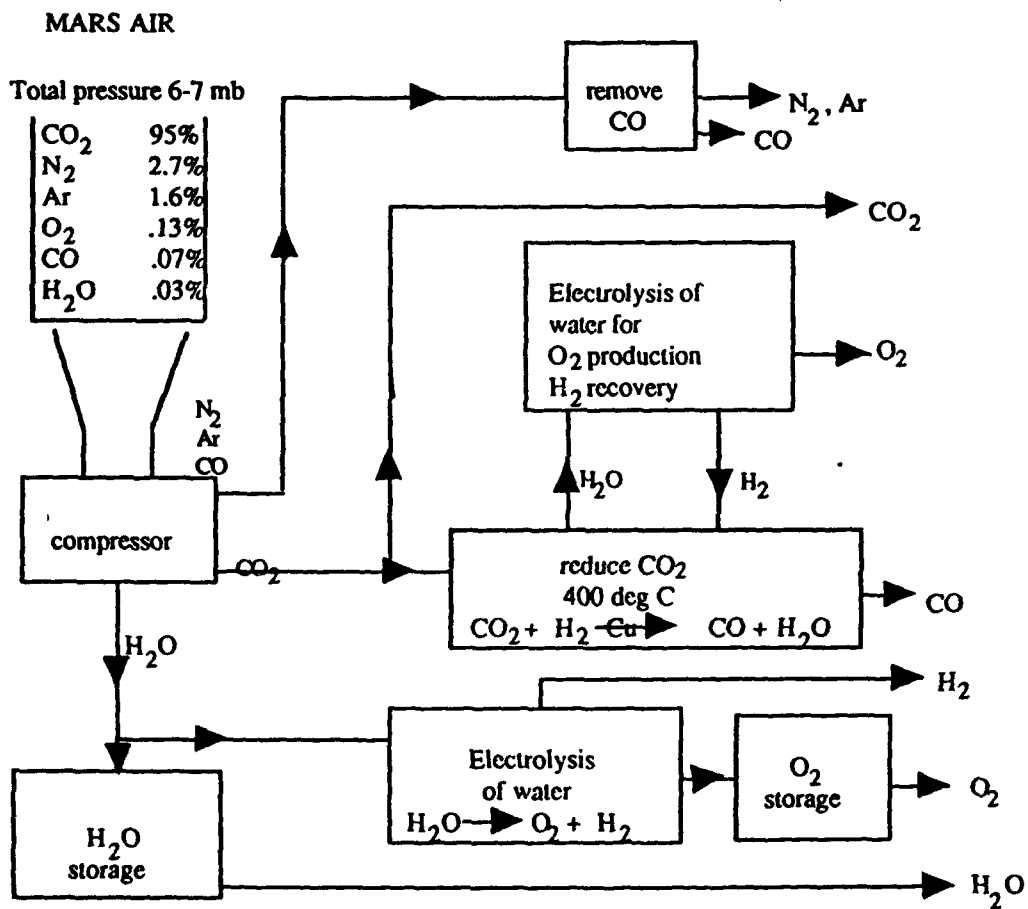
Figure 8. Martian Atmospheric Life Support Systems

The nitrogen/argon mix can be used as the buffer for respiration and the oxygen produced could provide astronauts with breathing air. Propellant manufacturing will require the use of the carbon monoxide, oxygen, and water. Drinking water also will be available but in small quantities. Electrolysis is not the only method for generating oxygen and others will be analyzed in the next chapter. Life support systems to convert the soil can be viewed in about the same manner as for the atmosphere, but advances in mining techniques need to be accomplished [Ref. 13:p. 2].

IV. OXYGEN PROCESSING SYSTEMS FOR THE MARTIAN ATMOSPHERE

Even though the Martian atmosphere is composed primarily of carbon dioxide, there is oxygen processing research underway and completed which converts carbon dioxide into breathable air for astronaut use during all types of Mars missions. Oxygen processor testing is presently being done in order to fulfill the requirements of the air revitalization functions of Space Station Freedom and future long term explorations.

This chapter will focus on several different oxygen processors which are made up of individual subsystems that provide for carbon dioxide reduction and oxygen generation. Although most testing performed today deals with closed loop regenerative systems, these oxygen processors most likely can be used as an open loop system by utilizing Martian atmospheric air as the input and oxygen as the output; this concept will be explored in this chapter.

A.   OXYGEN PROCESSORS

Since most carbon dioxide reduction and oxygen generating systems perform at various pressures different from that of the Martian atmosphere, compressors must be attached prior to air entry into the oxygen processor inputs. Filters must also be included in order to protect the systems from the dust contained in the Martian air. All the systems should also provide for a gas manifold in order to provide the required gas flow rates to

the processors. A simplified schematic of a modified oxygen processor for an open loop system is shown in Figure 9 [Ref. 19:p. 58].

```
Martian ──▶│ filter/ compressor │─│ gas    │─│ CO₂      │─│ O₂         │ O₂
  Air      │                    │ │ meter  │ │ reduction│ │ generation │──▶
```
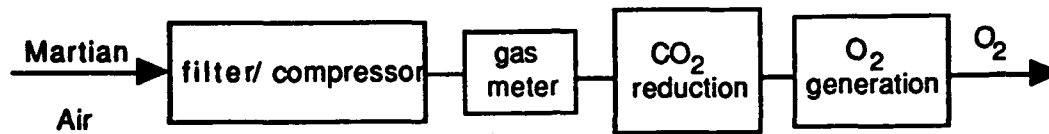
Figure 9. Open Loop Oxygen Processor

Most of the testing done and data obtained has been with the use of an electrochemical carbon dioxide removal subsystem in place of a compressor since present requirements call for closed loop systems. In order to satisfy an open loop regenerative system utilizing Martian resources, compressors will be used in order to transform the Martian air to system operating pressure prior to entering the processor subsystems. As long as the gas is metered at operating pressure and rate, the test results for the subsystems should be the same.

Since the Mars atmosphere is at a very low pressure of 8 millibars, a compressor is required to reach operating pressure of around 1013 millibars or 1 atmosphere which is the operating pressure of most oxygen processors. Of all the compressor types available, such as reciprocating, axial, and centrifugal flow, the latter appears to be the most suitable for use in the Martian environment [Ref. 15:p. 29]. The results of using a centrifugal type .8 efficiency compressor with respect to an isentropic compression cycle for one and two stages are shown in Table 10 [Ref. 15:pp. 227-228].

35

TABLE 10. COMPRESSORS AS AN AIR SOURCE

	INITIAL	HABITAT
Pressure	8 mb	1 atm
Temperature	253deg K	652 deg k
Enthalpy	$-8.76 * 10^3$ kJ/kg	$-8.37 * 10^3$ kJ/kg
Entropy S/R	2.9715	2.9715
Theoretical work		390 kJ/kg CO_2
		.11 kW-hr/kg CO_2
Real work (.9 efficiency)		.14 kW-hr/kg CO_2
Optimized in two stages		.07 kW-hr/kg CO_2

Prior to entering the cathode side of the electrolyzer, the gases should be blended to a desired ratio or rate according to the operating parameters of the system. This process is usually done in a gas manifold. The components of a manifold vary anywhere from filters, solenoids, needle valves for regulating flow, and rotameters in series with a mass flowmeter for readouts [Ref. 20:p. 9].

1. Solid Electrolyte Cell for Carbon Dioxide Electrolysis

The one advantage that the electrolyte cell has over most oxygen processors is that the cell has the capability to reduce carbon dioxide and perform water electrolysis for oxygen generation whereby other systems use two separate subsystems [Ref. 21:p. 2]. The purpose of the solid electrolyte cell is to electrolyze carbon dioxide into oxygen and carbon monoxide and to electrolyze water vapor into oxygen and hydrogen [Ref. 22:p. 4]. A modified block diagram of a open loop solid electrolyte cell and its various subsystems is shown in Figure 10 [Ref. 23:pp. 1-2].
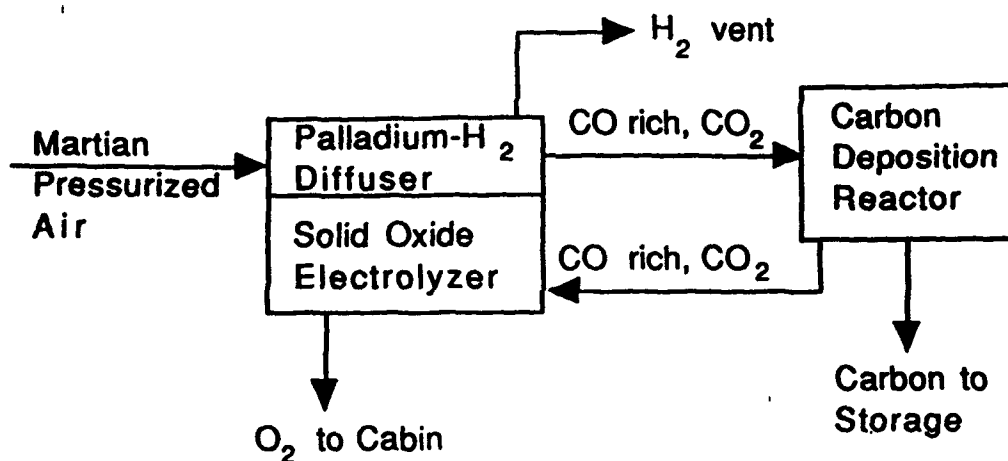
Figure 10. Modified Open Loop Solid Electrolyte Cell

a. Subsystems

(1) Palladium Hydrogen Diffuser. Since the carbon dioxide cell electrolyzer unit performs a water electrolysis function, hydrogen, which is a byproduct, must be removed from the system. The palladium hydrogen diffuser is a subsystem to the carbon dioxide electrolysis unit and is used to handle this task. It consists of palladium tubes in a cell bundle and a vacuum system that is manifolded to the open ended Pd tubes in the cold zone of the bundle. By having a vacuum applied to the palladium tubes, hydrogen produced by water electrolysis is removed by the diffuser through the Pd walls into the manifold and is exhausted through the vacuum pump [Ref. 20:p. 9].

(2) Solid Electrolyte Cell. The electrolyzer cell consists of a yttrium oxide stabilized zirconium oxide as the solid electrolyte [Ref. 21:p. 10]. For carbon dioxide electrolysis, the carbon dioxide gas enters the cathode compartment of the cell, where two moles of carbon dioxide react with four electrons to form two moles of carbon

37

monoxide and two oxide ions. The oxide ions migrate through the solid electrolyte and recombine at the anode to form one mole of oxygen gas and release four electrons. For water vapor, two moles of water react with four electrons to form two moles of hydrogen and two oxide ions in the cathode. The two oxide ions migrate to the anode to form one mole of oxygen and release four electrons [Ref. 21:p. 4]. A simplified version of the overall reactions which occur in the zirconium cell are shown in Figure 11 [Ref. 21:p. 5].
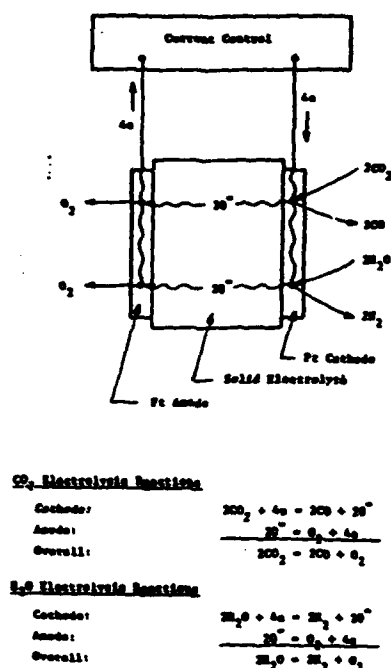
Figure 11. Descriptive Schematic of Carbon Dioxide
and Water Electrolysis Reactions

The electrolyzer cells operate at extremely high temperatures such as 900 degrees celsius. This prevents the formation of solid carbon in the cells while the reactions are taking place [Ref. 18:p. 3]. Design operating parameters for a one man capacity electrolysis unit is shown in Table 11 [Ref. 24:p. 12].

38

TABLE 11. DESIGN PARAMETERS FOR ONE-MAN CAPACITY ELECTROLYTE OXIDE CELL

Design conversion of CO_2	0.5 to 0.9 (i.e., 50 to 90% CO in cathode exit gas)
Gas flow rates at 25°C, 1 atm are	
CO_2 inflow	1,924 to 1,070 ml/min
CO outflow	962 ml/min
CO_2 outflow	962 to 107 ml/min
O_2 outflow	481 ml/min
Design operating temperature	850°
Gas flow rates at 850°C, 1 atm are	
CO_2 inflow	7,250 to 4,040 ml/min
CO outflow	3,630 ml/min
CO_2 outflow	3,630 to 404 ml/min
O_2 outflow	1,820 ml/min
Electrolyte disk	6.3 cm diameter
Electrode area per disk	20 cm^2
Current density	175 mA/cm^2
Amperes per disk	3.5 A
Number of disks	36
Theoretical power	~127 watts
Design electrolysis power efficiency	>0.5
Design electrolysis power	190 to 250 watts
Design current efficiency	~1
Estimated mass of electrolyzer and gas manifold tubes	2.3 to 5.5 kg
Disk composition	scandia-stabilized zirconia

(3) *Carbon Deposition Reactor.* The carbon monoxide rich cathode gas gets routed to the carbon deposition reactor which catalytically decomposes carbon monoxide into solid carbon and carbon dioxide according to the reaction:

$$2\,CO \xrightarrow{\quad 500\ degrees\ C\quad} C + CO_2$$

The solid carbon will be stored for further use if required and the carbon dioxide gets recycled back to the electrolysis unit [Ref. 23:p. 2].

b. Performance of a Three Man Capacity Oxygen Generating Breadboard Design

In the late 1980s, the testing of a 16 cell carbon dioxide electrolysis breadboard design which reclaims oxygen from carbon dioxide was performed in order to provide for a possible three to four person crew [Ref. 23:p. 13]. The inlet feed gas to the cells were manifolded and consisted of carbon dioxide, hydrogen, carbon monoxide, and nitrogen. The system also had 25 palladium tubes for hydrogen removal and the combustible exit gases, carbon monoxide and hydrogen, were burned at the electrolyzer cathode gas exit. The oxygen produced on the anode side flowed into a common manifold where the total oxygen flow is measured by a mass flow meter in the manifold exit stream. The oxygen was then vented into the atmosphere through a needle valve [Ref. 20:pp. 8-9].

The beginning of the test showed that an oxygen rate of 1.39 liters/min was measured at a current flow of 25 amps which amount to nearly 100% current efficiency. The palladium cells then developed a leak near the cathode gas inlet side of the active electrolyzer region due to thermal stresses. Despite the damaged cells, oxygen was produced at the constant rate of 1.3 liters/ min with a cathode feed gas flow of 4 liters/ min of carbon dioxide containing 2% hydrogen [Ref. 20:p. 12]. The measured

overall performance of the electrolysis testbed was near to the predicted one. A summary

of overall performance is shown in Table 12 [Ref. 20:p. 15].

TABLE 12. THREE-PERSON BREADBOARD PERFORMANCE

	Design	Actual
O_2 production	4.8 lb/day (minimum)	5.86 - 6.08 lb/day (at 250 mA/cm^2)
Average D.C. power:	528 watt (at 250mA/cm^2)	522 watt (at 250 mA/cm^2)
Current efficiency:	85% (minimum)	100% (~5 hours after start-up)
		85.3% average over 26 days
Total O_2 production during test period		25.2 lb/10 days
		94.9 lb/16 days
		120.1 lb
Total CO_2 consumption during test period		Seven 60 lb. ea.
		Cylinders of CO_2
		~420 lb.
DD=0.80 nominal		329 lb CO_2 as O_2 equivalent or 78.5% conversion of CO_2 to O_2
O_2 purity		
Start of test:		96.4% - balance CO_2
End of test:	100%	92.9% - balance CO_2
A.C. heater requirement	400 watt	750 watt

The test also showed that a better cell performance can be achieved with

greater voltages, which cause higher temperatures [Ref. 20:p. 14].

c. Conclusions

The 16 cell stack electrolyzer delivers oxygen for 3.75 persons at a

current density of 250 mA/cm-squared (16 lb oxygen/ person-day). A maximum DC

power consumption of 148 watts per person can be expected. Better systems are still under development and testing stages. In the future, one can expect the development of highly efficient carbon dioxide electrolysis systems for outer space and habitat use [Ref. 20:p. 15].

2. Bosch and Static Feed Water Electrolysis Oxygen Processor

The biggest difference between the Bosch and electrolyte cell methods for oxygen recovery is that the Bosch reactor's output is water not oxygen. This suggests that an independent water electrolysis subsystem must be attached to the output of the Bosch reactor in order to generate oxygen. Three types of water electrolysis subsystems under development are the Static Feed, Water Vapor, and Solid Polymer. Fortunately, a fully integrated system was successfully tested as a closed loop oxygen generator which united a carbon dioxide concentrator, a 12-cell Static Feed water electrolysis subsystem, and Bosch carbon dioxide reduction subsystem. Total testing time of the fully integrated system was 26.3 days [Ref. 25:p. 1]. A diagram that has been modified to fit the open loop oxygen processor concept is shown in Figure 12 [Ref. 25:p. 4]. Compressed Martian air at 1 atmosphere goes into a Bosch compressor/heater-reactor where it is first compressed to operating pressure; then carbon dioxide and hydrogen are transformed into carbon and water vapor [Ref. 22:p. 1]. The water is separated, collected, and used by the Static Feed subsystem to produce breathable oxygen for cabin use [Ref. 25:p. 26]. The remaining byproducts are recycled back to the Bosch compressor [Ref. 25:p. 22]. The water collected in the cabin is also recycled back into the static feed subsystem and the metabolic carbon dioxide is vented to the atmosphere.

42
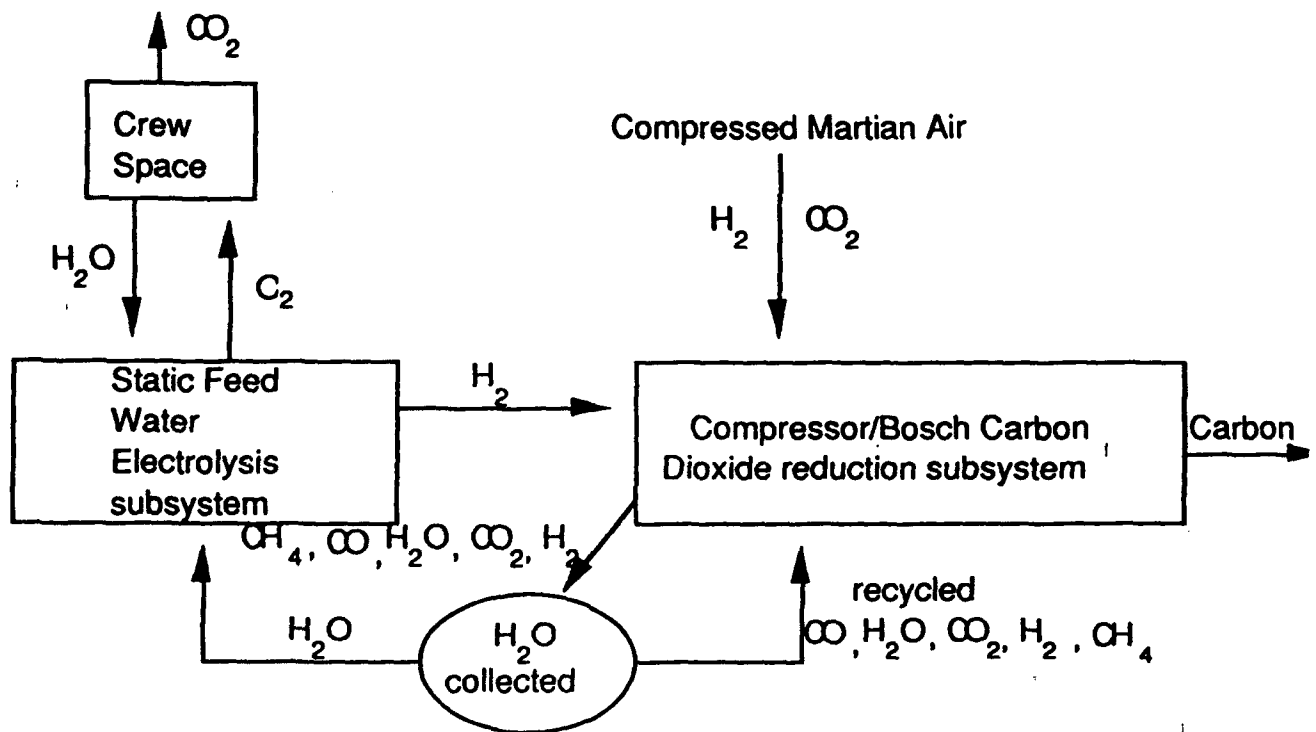
Figure 12. Open Loop Bosch Oxygen Processor

a. Subsystems

(1) *Bosch Reactor.* After the Martian air has been compressed to 1 atmosphere, it is sent through another compressor where it is compressed to operating pressure, then sent to the input side of one or two heat exchangers/reactors. These gases are preheated by the heat exchanger to 426-726 degrees celsius prior to reaching the reactor. Once reaching the reactor, one mole of carbon dioxide combines with two moles of hydrogen to form one mole of carbon and two moles of water vapor over a iron catalyst [Ref. 22:p. 1]. The overall reaction and pictorial of the Bosch process are shown
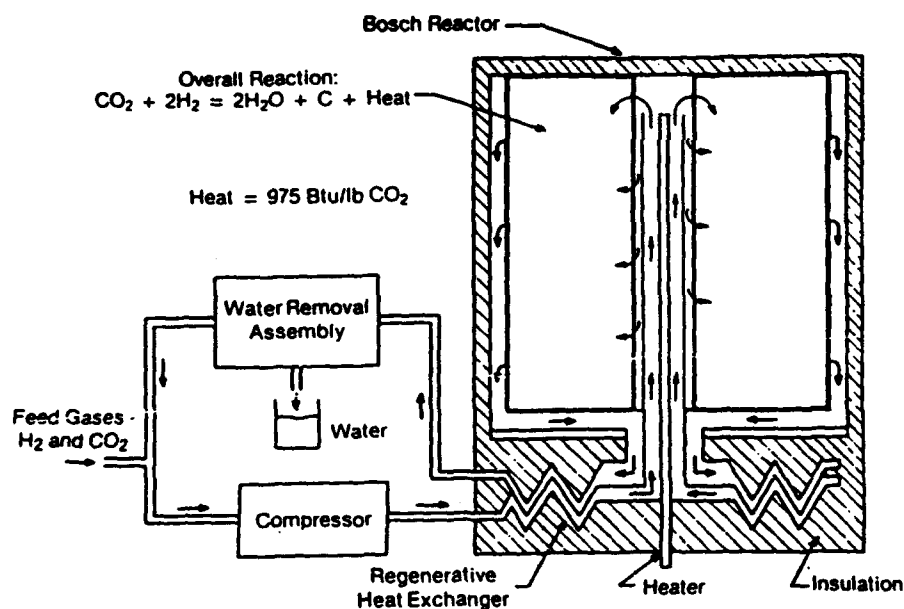
Figure 13. Bosch Technology Overview Bosch Process

in Figure 13 [Ref. 22:p. 2]. The reaction produces heat at 975 Btu/per lb of carbon

dioxide at 650 degrees celsius. With the Bosch, only 10% or less efficiencies are

attainable; therefore to obtain complete reduction with this process, the reactor must be

run in a recycle mode. The recycled gas mixture contains methane, carbon monoxide,

water vapor, hydrogen, and carbon dioxide. The intermediate reactions [Ref. 22:p. 1]

which form these are:

1. $CO_2 + C \longrightarrow 2CO$
2. $CO_2 + H_2 \longrightarrow CO + H_2O$
3. $CO_2 + 2H_2 \longrightarrow C + 2H_2O$
4. $2H_2 + C \longrightarrow CH_4$
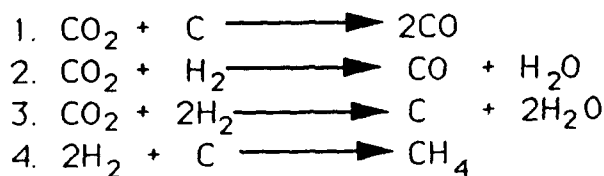
The solid carbon deposits on the catalyst and the catalyst - carbon cartilage is replaced

periodically by a fresh catalyst [Ref. 26:p. 6]. The recycled gases leave the Bosch at 922

44

degrees Kelvin and exchange heat with the incoming gases in a heat exchanger. The mixture then goes through a condenser/separator where the water vapor is continuously removed as liquid water. The recycled gases are then returned to the input side of the Bosch reactor [Ref. 25:p. 26]. Table 13 shows the operating conditions for a three man carbon dioxide reduction capacity [Ref. 27:p. 3].

TABLE 13. BOSCH-CRS NOMINAL DESIGN SPECIFICATIONS

Crew size	3
Nominal CO_2 reduction rate, kg/hr	.125
Feed gas pressure, kPa	130
Feed gas temperature, K	295
Feed gas humidity	
Relative humidity, %	74
Dew point temperature, K	289
Liquid coolant temperature, K	277
Purge gas	N_2
Purge gas pressure, kPa	310
Electrical power, VAC	115/200
Gravity	0 to 1

(2) Static Feed Water Electrolysis Subsystem. A static feed water electrolysis unit was chosen for the integration because it is simple, reliable and minimizes subsystem components and controls. By using this subsystem, the feed water is kept separated from the electrolyte cell and the bulk liquid electrolyte present is minimized in the water electrolysis unit [Ref. 25:p. 11]. There are two processes which occur within the static feed water electrolysis unit. The first one includes the electrochemical process of water electrolysis in an alkaline electrolyte. The second is the static addition of water to the module and its diffusion to the electrolysis site [Ref. 25:p.

15]. The general reactions which occur in the alkaline electrolysis cell and schematic of the cell itself are shown in Figure 14 [Ref. 28:p. 2].
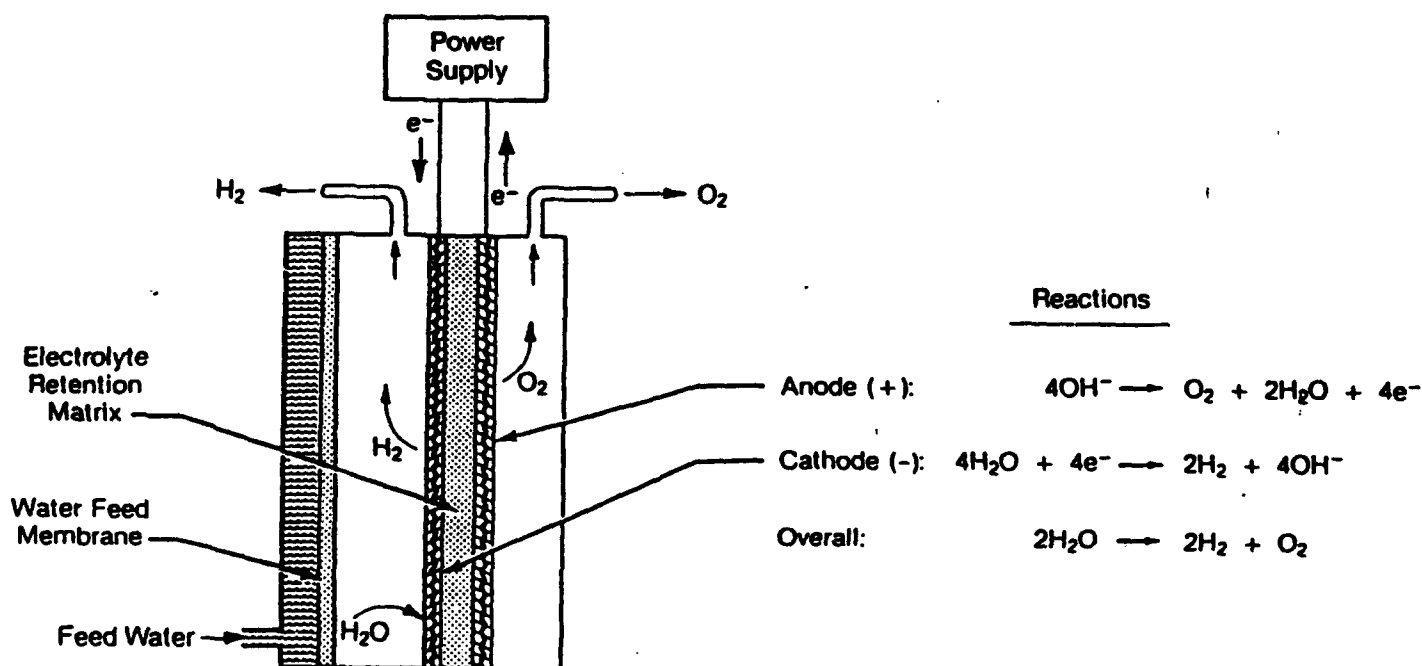
Figure 14. Schematic of Static Feed Electrolysis Process

The initial process starts with the water feed cavity filled with water and the electrolyte retention matrix fully charged with aqueous potassium hydroxide. Once electrical power is applied, water is electrolyzed from the electrolyte retention matrix creating a concentration gradient between the electrolyte in the water feed cavity and the electrolyte in the cell matrix. This causes water vapor to diffuse from the water feed matrix into the cell matrix due to this gradient. The consumption of water from the water feed cavity results in a static replenishment from the external water supply tank [Ref.

28:p. 4]. Design operating parameters for a one man oxygen capacity water electrolysis unit are shown in Table 14 [Ref. 29:p. 4].

TABLE 14. SFWEM DESIGN SPECIFICATIONS

Oxygen generation rate, kg/d	.68 to .91
Operating pressure range, kN/m^2	103 to 2067
Operating temperature range, K	ambient to 366
O_2 to H_2 pressure differential (max), $kN//m^2$	34.5
H_2 to water pressure differential (max), kN/m^2	34.5
Active cell area range, m^2	.0093 to .0186
Minimum number of cells per cm	1.2
Maximum matrix thickness, cm	.076
Performance, V	
at 108 mA/cm^2	1.7
at 215 mA/cm^2	1.9
Water feed mechanism	static
Gravity	0 to 1 G
Duty cycle	Continuous to cycle

b.   Integration Performance

The integration of a carbon dioxide collector, 4-Man Bosch carbon dioxide reduction subsystem, and a 2-Man static feed water electrolysis subsystem has been achieved and produced promising results. In order to collect the water from the Bosch Reactor, an automatic water collection system was attached to the Bosch reactor's condenser/ separator accumulator. About every 5.5 hrs, the accumulator upon reaching a certain level would be triggered by high level switches to discharge its water to the automatic water collection system and divert it into the static feed water electrolysis subsystem [Ref. 25:p. 58].

Each subsystem could be independently tested while integrated and any failure of one system would shutdown the others [Ref. 25:p. 60]. Each subsystem had its own nominal shutdown level parameters for temperature, pressure, and voltage [Ref. 25:p. 64].

The total system integration endurance test time was over 19 days or 457 hours and 245 hours was of continuous uninterrupted operation [Ref. 25:p. 74]. The integration flow conditions and test results for the carbon dioxide collector, water electrolysis, and Bosch reactor are shown in Tables 15 [Ref. 25:p. 55] and 16 [Ref. 25:p. 74].

TABLE 15. EDC/WES/BRS INTEGRATION FLOW CONDITIONS

System Location [a]	Species	Mass Flow Rate		Volumetric Flow Rate	
		kg/h	(lb/h)	dm³/min	(ft³/min)
1. Bosch Reactor	Carbon	0.045	(0.099)	-	--
2. Bosch Reactor	$H_2O(1)$	0.137	(0.30)	0.0023	(8.1×10^{-5})
3. Feed Gas/	H_2O	0.002	(0.004)	0.065	
Exhaust EDC	H_2	0.0095	(0.021)	1.85	(0.065)
	CO_2	0.167	(0.365)	1.52	(0.054)
4. Tylan Supply	H_2	0.006	(0.0132)	1.19	(0.042)
5. Loop Composition	Mixture $(H_2/CO_2/CH_4/CO/H_2O)$	3.08	(6.78)	73.6	(2.60)
6. EDC Anode	H_2	0.021	(0.046)	4.09	(0.144)
7. H_2 Flow	H_2	0.027	(0.059)	5.26	(0.186)
8. WES Exhaust	H_2	0.0117	(0.026)	2.27	(0.080)
	O_2	0.093	(0.205)	1.23	(0.043)
9. TSA	H_2	0.015	(0.033)	2.91	(0.103)
10. TSA	CO_2	0.167	(0.365)	1.52	(0.054)
11. EDC Condensate	$H_2O(1)$	0.103	(0.23)	0.00172	(6.1×10^{-5})

The results show that after 19 days of running, the Bosch reactor produced enough water on the average to satisfy 2.68 men per day. The oxygen generated during that time for respiration would satisfy on the average of 1.0 to 1.53 men per day

TABLE 16. INTEGRATED EDC/WES/BRS
ENDURANCE TEST RESULTS SUMMARY

<u>Bosch Reduction Subsystem</u>

Run Time, h	502
Total Carbon Cartridges	9
Total Carbon Collected, kg (lb)	15.3 (33.7)
Total Water Collected, kg (lb)	45.8 (100.8)
Average Man-Level (Carbon Calculated)	2.67
Average Man-Level (Water Calculated)	2.68

<u>Water Electrolysis Subsystem</u>

Run Time, h	822
Current Density, mA/cm^2 (A/ft^2)	108 (100)
Average Cell Voltage, V	1.58
Average H_2 Production, cm^3/min (ft^3/h)	905 (1.92)
Average O_2 Production, cm^3/min (ft^3/h)	452 (0.96)

<u>Electrochemical Depolarized CO_2 Concentrator</u>
<u>Subsystem</u>

Run Time, h	522
Current Density, mA/cm^2 (A/ft^2)	20.7 (20.1)
Process Air Temperature, K (F)	286 (56)
Process Air Dew Point, K (F)	283 (51)
Process Air Flow Rate, cm^2/min (ft^3/min)	310 (26)
pCO_2 range, Pa (mm Hg)	306 to 466 (2.3 to 3.5)
Average Cell Voltage Range, V	0.31

<u>Integrated System</u>

Run Time, h	457
CO_2 Removal Range, Man-Level	2.41 to 3.65
Oxygen Generation Range, Man-Level	1.02 to 1.53

with a electrochemical carbon dioxide removal subsystem in place [Ref. 25:p. 75]. The oxygen flow rate from the water electrolysis unit was .093 kg/hr or 2.323 kg/day [Ref. 25:p. 55].

There were several problems encountered during the testing period. Four operator -initiated and three system shutdowns occurred due to recurring high system back pressures. The cause was due to carbon buildup in the heat exchanger which broke off

and clogged up the Bosch reactor's condesor/separator. After a gas filter was placed prior to the separator, all operations continued without a problem [Ref. 25:p. 74].

c. **Conclusions**

The 1.02 to 1.53 range for oxygen generation man level values obtained is actually lower then if a compressor was attached to the system vice an electrochemical carbon dioxide removal subsystem. In order for the removal subsystem to operate, it requires hydrogen and oxygen [Ref. 25:p. 6]. The removal subsystem used up about a half of the oxygen generated by the WES. Without the removal subsystem in place, the 2.232 kg/ day of oxygen produced by the WES would have been used for respiration without leakage consideration. At a respiratory need of .83 kg/day-man, that equates to a oxygen man-level of 2.68 for the two-man capacity WES.

The testing perfor :d proved that a WES coupled with a carbon dioxide removal subsystem can be successfully integrated with a Bosch-based reduction subsystem to form a total oxygen recovery system. More development and testing of Bosch-based recovery subsystems is recommended for NASA by the testing facility, Life Systems Inc. The technology achieved by this could permit the selection of the optimum ECLSS for future manned long duration missions [Ref. 25:p. 2].

3. **Sabatier Oxygen Recovery System**

The Sabatier oxygen recovery system is just another method of regenerative life support of future long manned space missions. The Sabatier subsystem, as well as the Bosch, must have several subsystem components attached to it in order to produce

oxygen. Other subsystems needed for the Sabatier are the static feed water electrolysis unit and an carbon formation reactor to strip the hydrogen from the methane byproduct of the Sabatier reaction. A simplistic view of the entire Sabatier oxygen recovery system is shown in Figure 15 [Ref. 30:p. 282].
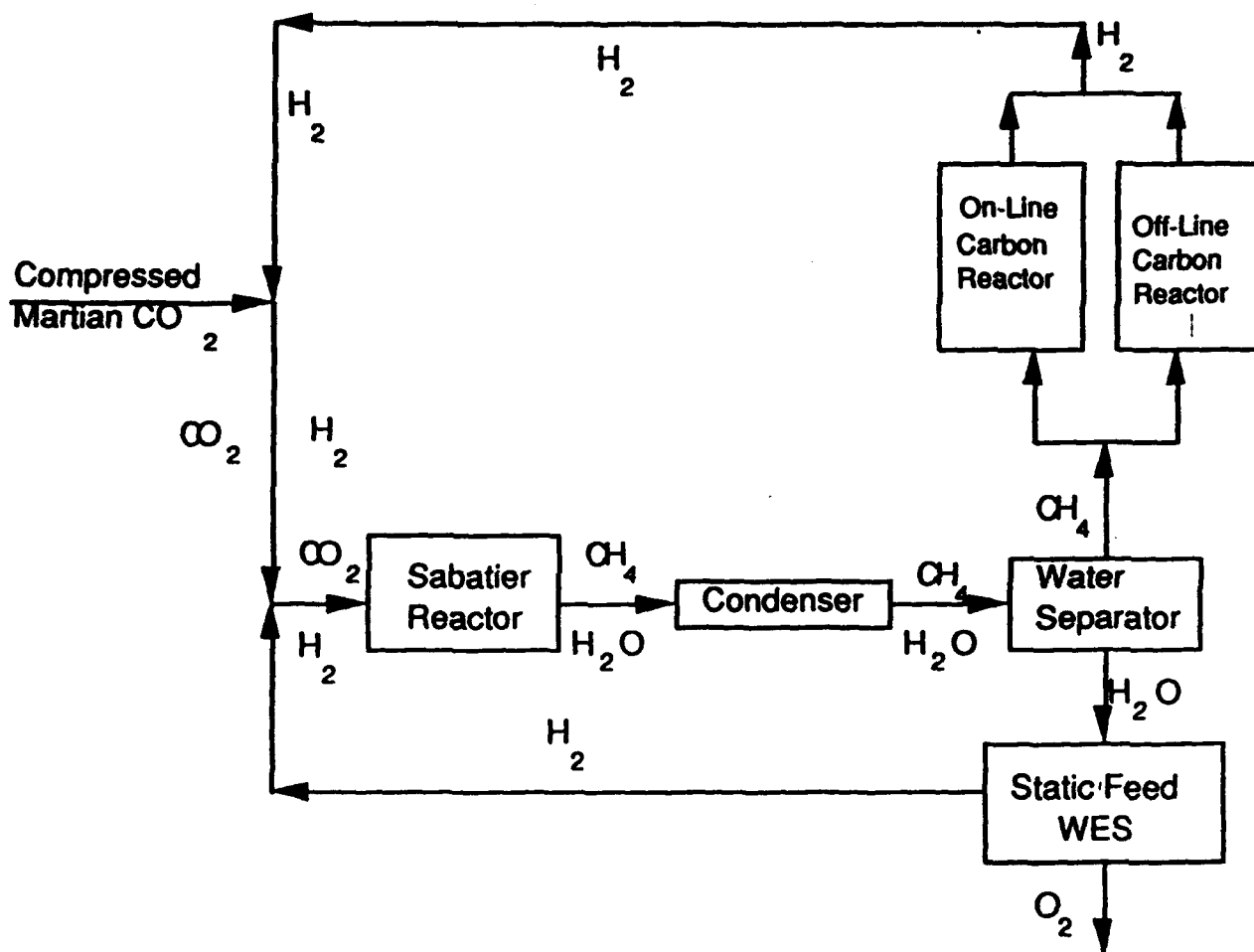

Figure 15. Sabatier Oxygen Recovery System

A mixture of compressed hydrogen and carbon dioxide from the Martian atmosphere is sent to the Sabatier reactor. After there, the water produced is separated via

51

a separator/condenser and sent to the water electrolysis unit for oxygen production. The methane is sent to the carbon formation reactor where carbon and hydrogen are split apart. The hydrogen byproducts from the ACR and WES are recycled back and mixed with the Martian air. Each subsystem has been well developed and even partially integrated; nevertheless, there has been no direct testing which produced results on the entire system shown in Figure 15 [Ref. 30:p. 282].

a. Subsystems

(1) *Sabatier Carbon Dioxide Reduction Subsystem.* After the carbon dioxide and hydrogen are mixed, they are sent through a charcoal filter to rid the gases of any trace amounts of contaminants carried over fron the other subsystems. The mixture is then sent to the Sabatier reactor over a ruthenium catalyst supported on alumina. The equation which takes place in the Sabatier reactor is as follows:

$$CO_2 + H_2 \rightleftharpoons CH_4 + 2H_2O + Heat$$
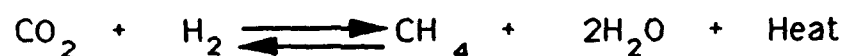
The heat produced by the reaction is around 20,000 Joules per gram of hydrogen reacted. The water vapor, methane, and excess reactant (hydrogen or carbon dioxide) travels to a condenser/separator where the water vapor is separated from the gas stream and sent to a accumulator for use by the static feed water electrolysis subsystem [Ref. 30:p. 1]. The water collected in the accumulator is dumped when full by a positive displacement pump at about 45 grams [Ref. 30:p. 4]. A schematic of the Sabatier subsystem and reactor are shown in Figures 16 and 17 [Ref. 30:p. 2].

Figure 16. Preprototype Sabatier Subsystem Schematic
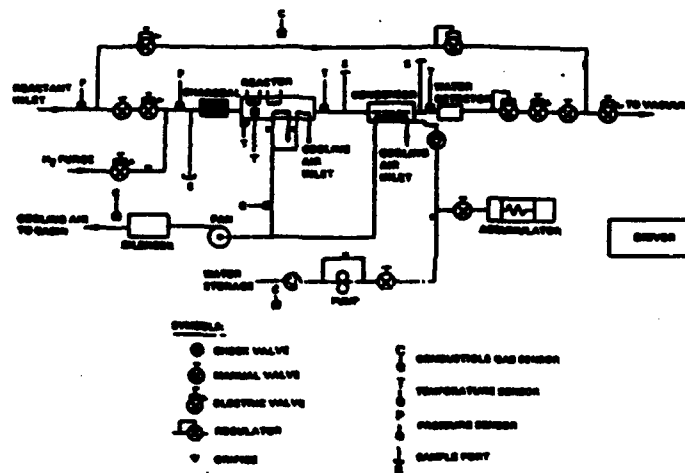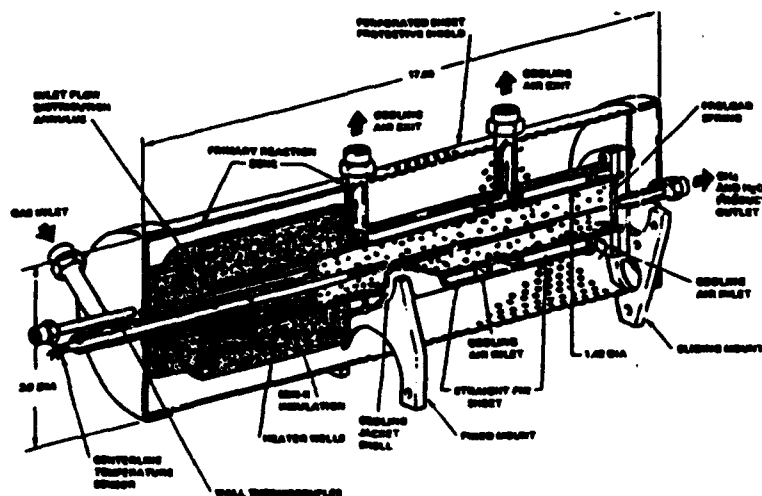

Figure 17. Sabatier Reactor - Cross Section

The design specifications of a 3-man carbon dioxide reduction Sabatier reactor are specified in Table 17 [Ref. 30:p. 3]. A rate of .125 kg/hr of carbon dioxide should produce 2.5 kg-water/ day (1.6 man-level water) [Ref. 30:p. 3]. The Sabatier reactor is temperature protected since the exothermic reaction which produces

53

temperatures around 593 deg C is reversed endothermic. The reactor converts more than 99% of the lean reactant in a carbon dioxide flow range of .91 kg/day to 3.6 kg/day. This represents a maximum flow for a three man nominal crew over a hydrogen-carbon dioxide molar ratio of 1.8 to 5.0 [Ref. 30:p. 3].

TABLE 17. DESIGN SPECIFICATIONS OF SABATIER

CO_2 flow rate	
Nominal (3 man)	125 g/hr
Minimum (1 man)	42 g/hr
Maximum (3 man cyclic)	213 g/hr
H_2/CO_2 molar ratio	
Minimum	1.8
Maximum	5
Reactor lean component efficiency	99%
Reactant supply pressure	1.4 atm*
Reactant supply temperature	18 - 24 deg C
Reactant dew point	Saturated
Touch temperature maximum	45 deg C
Water delivery pressure	2 atm
Start-up time maximum	5 min
Gravity	-1 to 1 g
Subsystem duty cycle	continuous to cyclic

* later revised to 1.24 atm

Molar ratios and pressure differences affect the hydrogen conversion efficiency. An example is that increasing the pressure from 1 atm to 1.4 atm will result in an increased hydrogen conversion of .1%. The minimum operating pressure with an automatic water removal system is 1.2 atm at a 3-man continuous condition with a molar ratio of 2.6. Also tests have shown that increasing the molar ratio will result in a corresponding increase in carbon dioxide conversion efficiencies [Ref. 30:p. 5]. A ratio

54

of 5.0 resulted in a 100% conversion of the carbon dioxide lean component. Studies have shown that an adequate cooling subsystem for the Sabatier reactor can efficiently handle reactant flows equivalent to a crew size of 30 people [Ref. 30:p. 6].

(2) Carbon Formation Reactor. The carbon formation reactor's (CFR) main purpose is to take methane produced by the Sabatier reactor and convert it to hydrogen and carbon. The hydrogen is then recycled back into the Sabatier and the carbon is periodically removed by the CFR. The CFR is still under development and a breadboard design has already been tested. The reaction which takes place in the CFR is described as follows:

$$CH_4 \longrightarrow C + 2H_2$$

The reactor is endothermic and has a conversion rate of more than 98% to carbon at temperatures above 960 deg C. A cutaway version of the quartz carbon reactor is shown in Figure 18 [Ref. 31:p. 763].

The CFR main advantage over the Bosch is that it packs carbon better [Ref. 32:p. 272].The breadboard CFR was a full scale design and sized for 45 man-days of carbon (12.3 kg). Carbon is formed on low density quartz wool and its growth was measured on a precision scale by reactor weight gain [Ref. 31:p. 763]. Methane flow rates ranged from 1-man (.36 kg-per day) to 6-man (2.2 kg-per day) [Ref. 31:p. 764]. 19 days of continuous testing showed a methane conversion efficiency varying between 88 to 92 %. A total of 11.7 kg of carbon was formed for a 3-man flow of methane [Ref. 31:p. 765]. A preprototype CFR is currently being developed for the Space Station Freedom
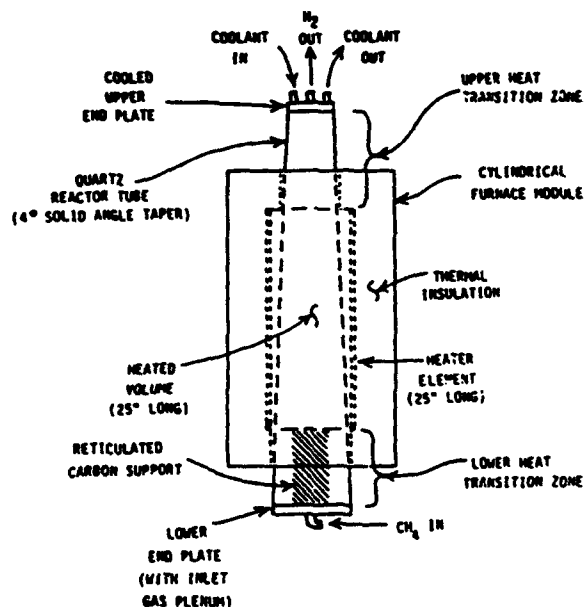
Figure 18. Breadboard CFR Cutaway

and will integrate the Sabatier and CFR. Projected operating temperatures are 1000-1100

deg C. Instead of only having one CFR, the design will have a carbon on-line producer

and an off-line in a change out sequence (cool, purge, remove carbon, install packing,

purge, reheat). This carbon formation reactor subsystem will be able to function on an

extended duration continual basis [Ref. 31:p. 767].

b. Conclusions

Even though this oxygen processing system has never been tested

together, its feasibility looks good on paper. The results of the combined CFR and

Sabatier testing should be out in 1992 and the last step should be to test with a water

electrolysis subsystem attached for a full oxygen generating system. The Bosch testing

results has already been presented early in this chapter. All three systems, electrolyte

oxide cell, Sabatier oxygen processor, and the Bosch oxygen processor, will be thoroughly evaluated in the next chapter in order to establish the most promising system for the Martian atmosphere.

V. SOLID OXIDE ELECTROLYTE CELL, BOSCH, AND SABATIER OXYGEN PROCESSOR QUICK-LOOK LEVERAGE ANALYSIS FOR THE NOMINAL SYSTEM OF THE MARTIAN MISSION.

A. INTRODUCTION

This study is an analysis of the Solid Electrolyte carbon dioxide electrolysis, Bosch reactor-static feed water electrolysis and Sabatier-static feed water electrolysis carbon formation reactor to see which system will perform the best as an oxygen processor for use in the Martian atmosphere. Detailed descriptions of the three processors can be found in Chapter IV. The subcomponents used prior to the processors such as compressors, filters, etc., have been excluded from this study since they were all common to the three. In order to satisfy the need of the trade study for system equality, the three systems were evaluated at a 4-man capacity level. The values necessary to do the study were only readily available at this capacity for all the subsystems. The analysis started off with an initial meeting at NASA Ames in early April with Vince Bilardo and Chris McKay. Betsy Dunsky, who has done other NASA trade studies, sat in on other meetings which followed and was assigned to help me. The evaluation parameters agreed upon to do the study were power, mass, volume, specific power, maturity, reliability, and resupply. The data used for the study were obtained through the SAS In House Technology Review databook at NASA [Ref. 30:pp. 236-319], Tim Falvey at Hamilton Standard, and The McDonnell Douglas Space Company. The leverage analysis used to determine the best system in this study is the same used by NASA Ames Life Support to evaluate similiar

systems [Ref. 33:pp. 1-11]. A breakdown of subsystem components used in this trade study can be found in Tables 18 [Ref. 34] 19 [Ref. 27:pp. 5-7] and 20 [Ref. 33:p. 8].

TABLE 18. ELECTROLYTE OXIDE CELL COMPONENTS

1. Electrochemical Module Cells
2. Pressure Controller Assembly
3. Thermal Control Assembly
4. Fluids Control Assembly

TABLE 19. BOSCH/SFWES COMPONENTS

1. Bosch Reactor w/ Heater
2. Condenser / Separator
3. Accumulator
4. Compressor
5. Water Pump
6. Pressure Regulator
7. Valves
8. Sensors
9. Packaging
10. Assembly, SFWES
11. Tank, Water Feed
12. Fluid Control Assembly
13. Heat Exchanger
14. Frame Mounting
15. Assembly-3 fluids Pressure Controller
16. Assembly, CCA

TABLE 20. SABATIER / SFWES /CFR COMPONENTS

1. Reactor w/ Heater
2. Condenser / Separator
3. Accumulator
4. Water Pump
5. Valves
6. Sensors
7. Pressure Regulator
8. Blower, Cooling Air
9. Restrictor
10. Packaging
11. Assembly, SFWES
12. Tank, Water Feed
13. Fluid Control Assembly
14. Frame Mounting
15. Heat Exchanger
16. Assembly-3 Fluids Pressure Controller
17. Assembly, CCA
18. 2 Electric Furnances

B. ASSUMPTIONS

Several assumptions were made during this analysis to ensure that all the oxygen processors were evaluated on an equal basis. They are as follows:

1.   100% conversion of carbon dioxide to water for the Bosch.

2.   Less than 100% conversion of carbon dioxide to water for the Sabatier, so assume that the remaining water required to even out with the Bosch comes from another source.

3.   Mass balance equations haven't been calculated.

4.   All systems are 4-man capacity.

5.   Compressors, filters, and manifolds have not been used in this study since all are common components.

6. No Sabatier resupply of hydrogen since the carbon formation reactor is also a supplier of hydrogen.

C. METHODOLOGY

The purpose of a quick-look leverage analysis is to provide us with a tool in the decision making process by using key evaluation parameters to compare two or more systems or methods against each other. For both specific power and volume leverage indices, the best value of each is normalized to one and the others are divided by it (i.e., if Option A has a mass of 300 kg and Option B has a mass of 100 kg, then Option A receives a normalization index of 3 and Option B receives an index of 1). This produces a set of dimensionless leverage indices for each 	 aluation parameter. The indices are then multiplied by a weighting factor assigned according to its importance to a particular mission (i.e., Mass for a particular mission may have a weight factor of 35% importance and volume 10%). The weight factors may be equal or unevenly assigned by the analyst, but all the weight factors must add up to 1. A total leverage rating for each parameter is then calculated. These total ratings are then compared to each other to see which one has. the lowest for that particular set of weight factors chosen. Leverage analysis will be used for a process technology trade-off study, so the oxygen processor which has the lowest index after all indices are added up is the best option.

In stepwise form:

1. The chosen evaluation parameters for this study are:
   L1 = Mass (kg), L2 = Specific Power (watt-hrs/ kg), L3 = Volume (cubic-meters), L4 = Resupply (kg/90 days), L5 = Maturity (1-8)

2. Mass was normalized by taking the mass of the system over its mass production per day, then dividing that by 90 days for an efficiency index. Resupply was normalized by dividing Resupply per 90 days by flow rate. Maturity was normalized by taking its level 1-8 (1-lowest development, 8-highest development) over 8 and subtracting 1 to achieve the lowest normalized number for the highest maturity. Specific power and volume best values were normalized to one and the others were divided by it as stated earlier.

3. Each parameter was then given a weight factor. This allows certain characteristics to be emphasized. If Power was difficult to obtain during a certain scenario, increase the Power weight factor so that an option with high Power consumption will have a higher Total Index. The sum of all the weight factors equals 1.
    w1 = .35 or 35% (Mass weight factor), w2 = .20 (Volume weight factor), etc.

4. Calculate the Total Leverage Index by adding the sum of each weight factor times its Index.
    $LT = w1*L1 + w2*L2 + w3*L3 + w4*L4 + w5*L5$

D. WEIGHT FACTORS

There is a set of equal weight factors to be used as a benchmark, and a set of sensitivities, where each individual leverage index is weighted at 50%, with all the others weighted equally at 10%. Finally there is one set of weight factors for a 90 day stay on Mars given by Chris McKay, a NASA Manager, who has been working on the Mars missions for quite some time. The weight factors can be seen in Table 21.

TABLE 21. WEIGHT FACTORS

Mission	Mass	Specific Power	Volume	Resupply	Maturity
Benchmark	20	20	20	20	20
Sensitivities	50	12.5	12.5	12.5	12.5
	12.5	50	12.5	12.5	12.5
	12.5	12.5	50	12.5	12.5
	12.5	12.5	12.5	50	12.5
	12.5	12.5	12.5	12.5	50
90-day stay	25	25	15	15	20

E.   RESULTS

The leverage indices which have been calculated based on actual values for mass, volume, power, etc. are shown in table 22. A leverage analysis spread sheet used in Table 23 was developed to calculate the best system for each set of weight factors.

The results for all weight factors in Table 24 show conclusively that the electrolyte oxide cell is the best oxygen processor. The parameters for that processor are unequivalently better than the other systems probably because it is the only self-containing unit for oxygen production in this study. It requires the least amount of equipment and processes to perform the same functions as the other two processors. The Bosch-WES system appears to be the better system when compared to the Sabatier-WES-CFR system except when resupply is heavily weighted.

The better system seems to be directly dependent to the number of subsystems used to make up the processor. Since the Sabatier has three, it is the worst of all the systems.

63

Some other parameters which could have changed the course of this study are cost, reliability, and maintainability. This information was not readily available since all subsystems are still under development.

TABLE 22. NORMALIZATION INDEX CALCULATIONS

	Mass (kg)	Specific Power (w*hr / kg)	Volume (m³)	Resupply (kg-90 days)	Maturity (1-8)
S1	298.6 a	$1.3 * 10^4$a	.77 a	18.7 b	6 b
S2	427.3 a	$1.54 * 10^4$a	.793 a	11.3 b	4 b
S3	3.18 a	3768 a	.0057 a	0 b	4 b
s1	.999 c	3.45 d	135.1	5.63 e	.25 f
s2	1.43 c	4.09 d	139.1	3.4 e	.5 f
s3	.011 c	1 d	1	0 e	.5 f

S1	=	Bosch / SFWES value
S2	=	Sabatier / SFWES CFR values
S3	=	Solid Electrolyte Oxide Cell values

s 1, 2, 3 = Normalized values

a = McDonnell Douglas data
b = Tim Falvey / Hamilton Standard data
c = calculated by [(mass system / mass day flow rate)/90 days]
    mass flow rate of a 4 man oxygen capacity is 3.32 kg/day
d = calculated by power / flow rate hour
    hour flow rate is .138 kg/hr
e = calculated by Resupply (kg-90 days)/flow rate daily
f = calculated by (1-maturity/8)

TABLE 23. LEVERAGE ANALYSIS

Mission	Component	Mass w1 Index	Spec. Power w2 Index	Volume w3 Index	Resupply w4 Index	Maturity w5 Index	Total Index
Bench-	S1	.20 * .999	.20 * 3.45	.20 * 135.1	.20 * 5.633	.20 * .25	29.1
mark	S2	.20 * 1.43	.20 * 4.09	.20 * 139.1	.20 * 3.4	.20 * .5	29.7
	S3	.20 * .011	.20 * 1	.20 * 1	.20 * 0	.20 * .5	.300
Sensitiv.	S1	.50 * .999	.125 * 3.45	.125 * 135.1	.125 * 5.63	.125 * .25	18.55
	S2	.50 * 1.43	.125 * 4.09	.125 * 139.1	.125 * 3.4	.125 * .5	19.1
	S3	.50 * .011	.125 * 1	.125 * 1	.125 * 0	.125 * .5	.318
Sensitiv.	S1	.125 * .999	.50 * 3.45	.125 * 135.1	.125 * 5.63	.125 * .25	19.47
	S2	.125 * 1.43	.50 * 4.09	.125 * 139.1	.125 * 3.4	.125 * .5	20.1
	S3	.125 * .011	.50 * 1	.125 * 1	.125 * 0	.125 * .5	.408
Sensitiv.	S1	.125 * .999	.125 * 3.45	.50 * 135.1	.125 * 5.63	.125 * .25	68.84
	S2	.125 * .143	.125 * 4.09	.50 * 139.1	.125 * 3.4	.125 * .5	74.55
	S3	.125 * .011	.125 * 1	.50 * 1	.1225 * 0	.125 * .5	.408
Sensitiv.	S1	.125 * .999	.125 * 3.45	.125 * 135.1	.50 * 5.63	.125 * .25	20.3
	S2	.125 * 1.43	.125 * 4.09	.125 * 139.1	.50 * 3.4	.125 * .5	19.84
	S3	.125 * .011	.125 * 1	.125 * 1	.50 * 0	.125 * .5	.314
Sensitiv.	S1	.125 * .999	.125 * 3.45	.125 * 135.1	.125 * 5.63	.50 * .25	18.27
	S2	.125 * 1.43	.125 * 4.09	.125 * 139.1	.125 * 3.4	.50 * .5	18.75
	S3	.125 * .011	.125 * 1	.125 * 1	.125 * 0	.50 * .5	.501
90 day	S1	.25 * .999	.25 * 3.45	.15 * 135.1	.15 * 5.63	.20 * .25	22.27
Mars	S2	.25 * 1.43	.25 * 4.09	.15 * 139.11	.15 * 3.4	.20 * .5	22.86
Mission	S3	.25 * .011	.25 * 1	.15 * 1	.15 * 0	.20 * .5	.50

TABLE 24. RESULTS

Mission Weight Set	"Winning" Component
Benchmark (Uniform Weighting)	System 3
Sensitivities	System 3
	System 3
	System 3
	System 3
	System 3
90 Day Mars Mission	System 3

65

F. CONCLUSIONS

In conclusion, this "quick look" leverage analysis of the three oxygen processors seems to be a reasonable way today of comparing existing life support process technologies. The technology to use for a particular NASA mission will be dependent on when the technology is required. Since the Mars mission is years away, the Bosch-WES processor seems to be the better system for present missions like the Space Station. The electrolyte cell is not as fully developed as the others; it may prove to be the better system for the Mars missions.

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69

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